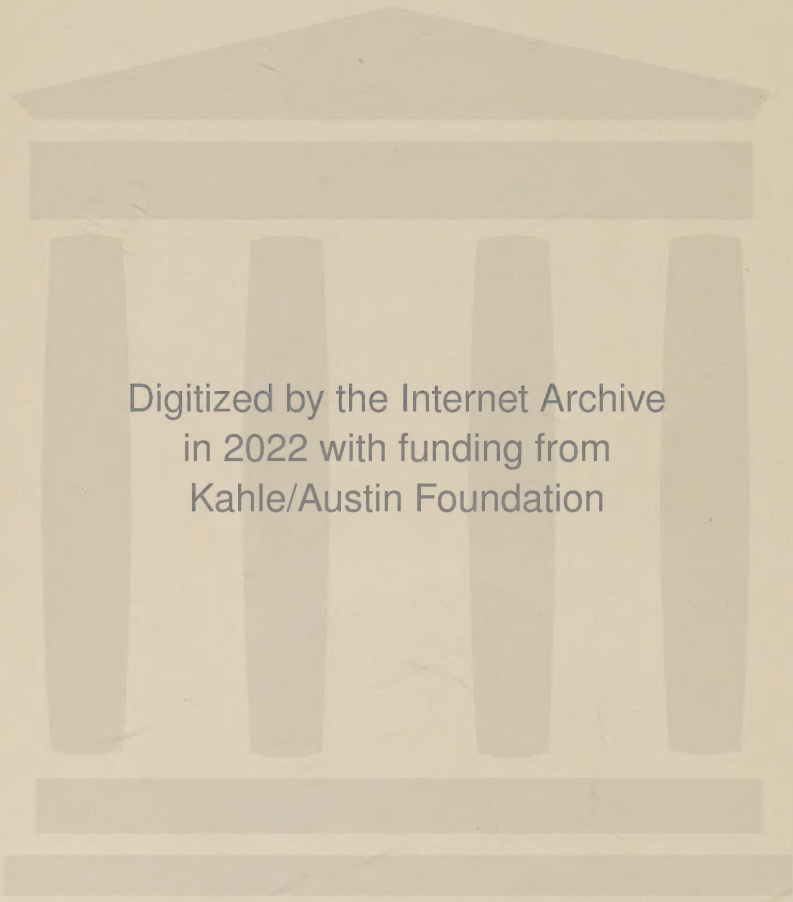


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QUATERNARY CLIMATES

GEOLOGIC HISTORY OF LAKE LAHONTAN

By J CLAUDE JONES

ON THE PLEISTOCENE HISTORY OF THE GREAT BASIN

By ERNST ANTEVS

THE BIG TREE AS A CLIMATIC MEASURE

By ERNST ANTEVS

TREE GROWTH AND CLIMATIC INTERPRETATIONS

By ELLSWORTH HUNTINGTON



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EDITORIAL NOTE

It is to be expected that the papers of three investigators, even though relating to the same subject, should present somewhat divergent views. In spite of such divergence, it has been thought desirable to incorporate the papers of Doctors Jones, Antevs, and Huntington in one volume, so that the reader may study their independent views.

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THE GEOLOGIC HISTORY OF LAKE LAHONTAN.

BY J CLAUDE JONES

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University of Nevada.*

Twenty-two Figures.

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GEOLOGIC HISTORY OF LAKE LAHONTAN

INTRODUCTION.

Among the more obvious geological features of the Great Basin are the well-preserved terraces, bars, and sediments formed by the Quaternary lakes that formerly occupied many of the valleys. Lake Lahontan is especially noteworthy, both on account of the wide area covered by its waters and the excellent preservation of the lacustrine sediments and topographic features displayed in its desiccated basin.

As shown on the accompanying map (fig. 1), the hydrographic basin of Lake Lahontan covered an area of about 45,000 square miles in northern and western Nevada, with small areas in the adjoining States of California and Oregon. The area included many elongate and more or less isolated mountain ranges rising 3,000 to 6,000 feet above the intervening valleys and with a general north-and-south trend. The general elevation of the valleys is approximately 4,000 feet above sea-level. Low divides, frequently formed of alluvium washed from the mountains, separate and subdivide the area into many independent basins.

Only the valleys in the western portion of Nevada were occupied by Lake Lahontan. The great peninsulas and islands formed by the mountain ranges impressed an exceedingly irregular shore-line upon the lake. At the time of the greater expansion of the water-surface it covered an area of about 8,500 square miles, and as the surface of the lake fell and uncovered the different divides it separated into a number of independent smaller bodies of water. At present these subsidiary basins are in all stages of desiccation. Some retain permanent bodies of water, such as Pyramid, Winnemucca, and Walker Lakes; others may go entirely dry in exceptionally dry years, as Carson, Honey, and Humboldt Lakes; still more are playas, covered with water for only brief periods of the year, as the Black Rock and Smoke Creek Deserts.

The Lahontan Basin was visited by King during the early seventies and by Russell a few years later. They concluded that Lake Lahontan existed during the Pleistocene and possibly was contemporaneous with the different stages of glaciation known at the time. During the years 1913 and 1914 the present writer was led to a restudy of the basin through an investigation of the potash deposits in Nevada.

The field work, in part made possible through the kindness and financial aid of Dr. D. T. MacDougal, was largely done during 1914 and 1915. The main results of the study were given at a meeting of the American Association of Geographers in 1916, but other duties have prevented publication until now.

SUMMARY.

Among the deposits of the old lake, the most important in deciphering its history are the deposits of lime carbonate or tufa found throughout its basin. Fortunately, considerable evidence pointing to the method of origin of the calcareous deposits removed the necessity of considering the ancient lake to have been a body of highly concentrated saline water, as had been thought by King and Russell.

An estimate of the amount of tufa deposited by the ancient lake corresponded very closely to the amount that apparently should have been deposited, assuming that the calcium carbonate carried into the old lake bore to the alkalies the same relation that prevails at present in the waters of the Truckee River. Corroborative evidence that Pyramid and Winnemucca Lakes are remnants of Lake Lahontan¹ is found in the work of Snyder on the fishes in Pyramid Lake. A determination of the age of Pyramid and Winnemucca Lakes, based on the amount of contained salts and the present rate of accumulation, indicates that their entire history is within the last 3,000 years.

It was further found that Walker Lake did not come into existence until Lake Lahontan had reached the high-water stage. A similar determination of the age of Walker Lake indicated that it began to form about 1,000 years ago, suggesting the time that Lake Lahontan reached its maximum height. These figures check fairly closely with the world-wide work of Huntington on the dating of changes of climate during the past few thousand years.

The remains of several large animals, members of the Pleistocene fauna and now extinct, have been found in the lake beds. This would seem to indicate that at least some of the fauna lived well into historical times.

PREVIOUS WORK.

The first serious study of the Lahontan Basin was made by the geologists of the Fortieth Parallel Survey. In the final report, King² gave the ancient lake its present name and accurately described the masses of calcareous sediments, or tufa, found coating the rocks of the area that had been bathed by the lake waters. Noting many of the peculiarities of the tufa deposits and, witnessing the formation of gaylussite in the Soda Lakes near Fallon, he believed they originated under analogous conditions. Through experiment he discovered that when gaylussite is placed in fresh water, the soda is leached, leaving the calcium carbonate in a fine granular mass, retaining the general outline of the original crystals of gaylussite. As the gaylussite forming in the Soda Lakes builds up masses that resemble in miniature the deposits of tufa occurring in the Lahontan Basin, King believed that the tufa was originally deposited as gaylussite. While he had determined that there was no outlet to Lake Lahontan in the parts of its basin he examined, yet reports of a channel to the south led him to believe that the lake had overflowed at one time in its history.

In harmony with his evidence, King³ sketched the history of the ancient lake as follows: In the beginning the lake basin filled possibly to the level of overflow; in time the waters became concentrated through evaporation and, as the level of the lake fell, eventually became approximately as saline as the present Soda Lakes. With the continued desiccation, the tufa was deposited as masses of gaylussite, and the lake may have completely disappeared. A following period of increased humidity caused the basin to fill once more, and as the lake rose above the outlet, the dissolved salts were carried out of the

¹ In this paper the name "Lake Lahontan" has been restricted to the lake that gave rise to the terraces, bars, tufa, etc., at present visible. No account is taken of previous lakes that may have occupied its basin. The correlation of its history with the histories of the other ancient lakes of the Great Basin, such as Bonneville, is postponed for further study.

² Clarence King, U. S. Geologic Surv., 40th Par., vol. 1, p. 490, 1878.

³ Op. cit., pp. 521, 522.

basin and the gaylussite leached, leaving the tufa as pseudomorphs of the original deposits. The lake again evaporated and left only the comparatively fresh lakes, at present in the basin as the last stages in the evaporation of the second great lake.

A few years later, Russell made a thorough study of the entire basin formerly occupied by Lake Lahontan. His final report¹ covers the field in detail with an accuracy of description that is an inspiration to those who follow in his footsteps. Russell determined that at no point was there any outlet to Lake Lahontan and that it could not have overflowed at any stage, as King had postulated. In the midst of the lacustrine sediments exposed along the banks of the Truckee, Humboldt, and Walker Rivers he observed a layer of sands and gravels which he denominated as the "medial gravels," that were apparently deposited during a low-water stage in the history of the lake. He recognized three types of tufa in the Lahontan Basin: the lithoid, stony, and compact; the dendritic, coralline, and porous; and the thinolite, with the crystal form of an unknown mineral, but now replaced by granular calcite. While Russell recognized that there was more or less mingling of the lithoid and dendritic tufas, yet he believed that in the main the different types occurred throughout the basin in distinct layers. According to his description, the lithoid tufa occurred at the bottom, in immediate contact with the rocks on which it was deposited as a solid, compact film, 6 inches thick at the water-level of the present Pyramid Lake and, gradually decreasing in thickness for over 500 feet above, disappearing just below the highest water-level reached by Lake Lahontan. The thinolite was deposited directly on the lithoid tufa, beginning as a coating nearly 5 feet thick on the thinolite at the water's edge and gradually decreasing in thickness up to the thinolite terrace, 110 feet above the present level of Pyramid Lake. The dendritic tufa in turn was deposited on the thinolite and, overlapping it, extended to an elevation of 320 feet.

While a large part of the tufa was deposited in contact with the rocks, much of it occurs in large columnar masses which Russell called tufa domes. Observing a dome in Mono Lake that had a fresh-water spring coming from its center, and witnessing the formation of miniature domes about the outlets of hot springs at the northern end of Pyramid Lake, he assumed that all of the domes had had a similar origin. Believing that the remainder of the tufa was a chemical deposit from the lake waters, and noting that calcium was promptly deposited as it was carried into Great Salt Lake, Russell thought that the waters of Lake Lahontan might have approximated the composition of the present Great Salt Lake when the tufa was being deposited. He notes, however, that this conception was contrary to the evidence of the comparative freshness of the lake waters suggested by the abundance of fossils found associated with the tufa. As there seemed to be a marked difference in the character of the lithoid and dendritic tufas, he assumed that the composition of the Lahontan waters was probably somewhat different at the times they were deposited.

The present lakes occupying the depressions in the Lahontan Basin are comparatively fresh and, in accord with his hypothesis, could not be the concentrated remnants of a more saline lake. Estimating the age of Walker Lake

¹ I. C. Russell, *Geologic History of Lake Lahontan*, U. S. Geol. Surv. Monograph 11, 1886.

and of the basin as a whole by determining the rate at which the salts were being carried in at the present time, he thought that the few hundred years necessary was too short a period to compass the entire history of Lake Lahontan. In accord with his hypothesis it was necessary to assume that the former lake had been completely desiccated and that the deposited salts had been buried under the alluvium washed into the basins from the surrounding mountains before the formation of the present lakes.

Russell concluded that the history of Lake Lahontan began with a period of greater humidity than the present, during which the basin filled to the highest beach-level. A drier period following, the lake receded, concentrating the salts dissolved in the water and causing the deposition of the lithoid tufa. The medial gravels were presumably deposited during this low-water state, and there was a possibility that the lake became completely desiccated. A second humid period followed and the lake basin again filled nearly to its former high-water mark. Again evaporating, the thinolite and dendritic tufas were deposited and the lake water completely disappeared, leaving the lower depressions covered with the deposits of salts. These in turn were buried beneath the clays washed in from the sides of the valleys and protected from solution by the waters of the present lakes.

TUFAS OF THE SALTON BASIN.

Some 10 years ago the writer was able to observe the formation of tufa in the present Salton Sea and to make a study of the older tufas found in its basin. It was found ¹ that the tufa now forming was being deposited through the activities of blue-green algæ, with the possible assistance of associated bacteria, and considerable corroborative evidence was gathered from the older tufas.

As will be noted from the preceding abstracts, the interpretation of the history of Lake Lahontan has been almost entirely determined by hypotheses advanced to account for the origin of the tufas. Russell ² admits that the physical evidence alone is inconclusive and, were it not for his interpretation of the origin of the tufas, it would have been impossible for him to give the history in full. During the following years Weed's ³ observations on the deposition of travertine around the orifices of hot springs at Yellowstone Park through the agency of algæ caused Russell ⁴ to suggest that the tufas of Lake Lahontan might have had a similar origin. With the knowledge of the origin of tufa gained in the Salton Basin, it is evident that if the tufas of the Lahontan Basin had had a similar origin the history as accepted to the present might be in need of revision.

RECENT TUFA IN SALTON SEA.

In order that all the evidence bearing on the origin of the Lahontan tufas may be before the reader, it is necessary to review the data obtained in the Salton Basin. The recent tufa formed in the present Salton Sea is found as a coating covering the submerged twigs and branches of the plants killed

¹ J. C. Jones, Carnegie Inst. Wash., Pub. No. 193, pp. 79-83, 1914.

² I. C. Russell, U. S. Geol. Surv. Monograph 11, p. 171.

³ W. H. Weed, U. S. Geol. Surv., 9th Ann. Report, pp. 619-681, 1889.

⁴ I. C. Russell, Bull. U. S. Geol. Surv. No. 108, pp. 94-95, 1893; *Lakes of North America*, p. 112, 1897; *Present and extinct lakes of Nevada*, Nat. Geog. Soc. Mon. No. 1, p. 115, 1895.

during the rise of the lake in 1906-7. When this deposit is first taken from the water it is soft, gelatinous, and dark greenish-gray in color. As it dries it becomes lighter in color, hardens, and assumes the characteristic appearance of a tufa. The deposit is about a millimeter in thickness and is built up of a multitude of protuberant individuals that give the surface a roughened appearance. The individual deposits vary in size at the base up to a maximum diameter of 5 mm. and, expanding in their outward growth until they coalesce toward the surface, form a fairly uniform coating with occasional interspaces where no deposit has formed.

Examining the dried material under a hand lens, it was found that the surface was partly covered with a mat of the free ends of filamentous algæ whose bases were buried in the tufa. The algæ were separated from the tufa by dissolving the calcium carbonate in weak acetic acid and were submitted to Mr. C. L. Brown, of the University of Nevada, for identification. He reported that they were blue-green algæ belonging to the genus *Callothrix* and probably either *C. thermalis* or *C. parietina*.

In figure 10 (a transverse section of the tufa) the algæ may be seen as the slender dark threads embedded in the mass of calcium carbonate. The latter is minutely crystalline, and while it is possible to occasionally recognize individual crystals of calcite under the highest power of the microscope, the greater part of the deposit was a cloudy aggregation of submicroscopic particles. These are attached to the algæ threads, leaving the interspaces largely unoccupied. The tufa is very porous and corresponds in all essentials to the dendritic type recognized by Russell. In a former paper¹ it was shown that its chemical composition is strikingly similar to that of the tufas of the Great Basin and to a marl that has been formed through the agency of similar algæ.

The tufa is formed only on the submerged branches and stems of the dead shrubs still standing near the shores of the lake, and as a coating on the rocks of a few volcanic hills that were partly submerged at the time. Elsewhere the shores and bottom of the lake were formed of soft muds and the failure of the tufa to form except where it had a firm support is in harmony with the observations of Russell² in the Lahontan Basin. Although search was made for oolitic sands, cemented sands, or other evidence of a general deposition of calcium carbonate, none was found. The yearly chemical analyses show that the waters of the lake contain no carbonates, all of the CO₂ being either free or in solution as bicarbonates. The deposition of the tufa is indicated by the relative decrease of both the calcium and carbonic-acid radical each year. Assuming that all of the CO₂ is combined with calcium, the waters have approximated the limit of solubility of calcium bicarbonate, but as no general deposit of calcium carbonate can be found, it is necessary to conclude that the deposition of the tufa must be due to some cause other than to simple supersaturation of the lake waters.

OLDER TUFAS IN THE SALTON BASIN.

The tufas deposited by the former lake, Blake Sea, that filled the Salton Basin are similarly limited in their distribution to the points where the waters washed the solid rocks. The most typical area is at Travertine Point, near

¹ J. C. Jones, Carnegie Inst. Wash. Pub. No. 193, p. 80.

² I. C. Russell, U. S. Geol. Surv. Monograph 11, p. 219.

the northwestern shore-line of the old lake. The point is composed of several granite hills that were nearly submerged by the ancient lake and connected with each other and the mainland by bars of granitic sand. The outermost hill rises as a steep talus slope, composed of huge granite boulders up to 10 feet in diameter. In the recesses between the boulders it is sometimes possible to penetrate 20 feet or more from the surface of the slope.

On the outer surfaces of the boulders the tufa is 30 inches thick over a vertical range of 120 feet, but gradually grows thin toward the top until at the high-water level it is but a thin film. Where it is thick it is dendritic and is composed of an anastomosing mass of thin plates, or rudely circular columns, approximately 3 mm. in thickness. As it thins toward the former high-water mark it becomes more compact and the thin film at the top is a typical lithoid tufa.

On the sides of the boulders and back into the recesses, the tufa also becomes thinner until, in the darker places, it has become a thin film of lithoid tufa. The most striking character is the decided tendency of the tufa plates and columns, in the recesses along the sides and bottoms of the boulders, to turn upward and outward toward the light. This is especially well shown in the accompanying photograph (fig. 12).

The dendritic tufa contains many snail-shells embedded throughout its mass, suggesting that the animals lived on the surface of the growing tufa. Considerable sand is also found in this tufa, in part embedded in it and in part filling the open spaces. The lithoid tufa is much purer and contains very little sand and no shells. Both types of tufa are banded, the bands being much broader in the dendritic type, indicating its more rapid growth.

In the thin sections of the tufa certain structures were observed that bore striking resemblance to the algæ found in the Recent tufa. In rare instances the remains of algæ with a faint green color were seen to be still preserved beyond question, and these may be readily seen in figure 11 as the dark lines radiating from the curved outlines of the bands.

ORIGIN OF THE TUFAS OF THE SALTON SEA.

In considering all possible hypotheses in harmony with the extreme local development of the tufas, the utter lack of any other form of contemporaneous deposit that would even suggest a general saturation of the lake waters with calcium carbonate, the evident relation between the character and depth of the deposits to light and other conditions favorable to the growth of the plants, the constant presence of the algæ in the tufas, it was concluded that the formation of the tufas was primarily due to the activities of the algæ. The formation of calcareous deposits by this especial group of algæ has long been known in other situations, as will be considered in detail later; but as far as known to the writer, no one has yet been able to determine the details of the process.

RECENT TUFA IN PYRAMID LAKE.

On carrying the study to the Lahontan Basin it was found that a deposit of tufa is forming at present in Pyramid Lake. This consists of a thin layer covering the exposed surfaces of approximately 50 per cent of the rocks and

gravels along the shores and extending from an elevation of 12 feet above the water's edge to an unknown depth beneath the surface of the lake. Where this layer is submerged it is covered with a thick growth of algæ. In no case was the deposit found under the water in the absence of the algæ, although as many instances were noted of submerged rocks where no deposit had yet formed.

The assistance of Mr. C. L. Brown, a botanist especially familiar with the algal flora of Nevada, was secured and in a study of the forms associated with the recent tufa he was responsible for their identification.

At the water's edge a long filamentous green alga, a species of *Cladophora*, grows as a fringe 6 to 9 inches long in a narrow band about equally divided above and below the water. When the level of the lake falls, this dries, bleaches, and forms a grayish-white, paper-like band clinging to the rocks. In 1913 there were two of these bands, respectively 30 inches and 6 feet above the present surface of the water, marking the former level of the lake in recent years. As far as could be observed, these algæ were not forming calcareous deposits, as many instances were noted where they grew directly on the rocks. Below this band a grayish-white alga, another species of *Cladophora*, with much shorter filaments, grew in tufts and bunches that had their bases so firmly fixed in the layer of recent tufa that pulling the algæ from the rocks brought the tufa layer with them. At the base of the tufts was a narrow zone of blue-green algæ that included species of *Callothrix*, *Nostoc*, and *Formidium*. On the under side of projecting rocks and older tufa the same blue-green algæ were found growing in the absence of the *Cladophora*, and with their bases firmly fixed in a thin film of calcareous deposit. Similarly, at depths of 4 feet and over, the blue-greens grew in the absence of the other algæ, and in every instance in constant association with the recent tufa. It would seem that the blue-green algæ require a somewhat diffused light and that they are unable to grow at or near the surface of the water unless protected and shaded from the direct sunlight by the other algæ or the rocks. The other forms of life found associated with the algæ growing on the recent tufa were snails, diatoms, fresh-water sponges, insect larvæ, crustaceans, and other forms of aquatic life. It is noteworthy that the snails were the same species found in the older tufas and that at present both the shells and the living animals are most abundant on the under side of the projecting ledges.

On the surface of rocks that have no other deposit, the Recent tufa forms a film up to 2 or 3 mm. thick. Where the deposit is very thin it can be seen to begin as a multitude of separate rounded points that rapidly increase in diameter, meet, and coalesce. As the deposit thickens it becomes solid, compact, and stony, and is a typical lithoid tufa.

Under the microscope thin sections of the recent tufa show that it is made up of a number of thin layers more or less parallel to the rock-surfaces on which they were deposited. These layers vary somewhat in thickness parallel to the rock surface, giving them gently undulating outlines, and produce the small nodules on the surface of the deposit. As in the tufa of the Salton Sea, the mass is composed of exceedingly minute particles, and but rarely could individual crystals be recognized. Fragments of the algæ were abundantly scattered through the tufa, and in the thicker portions of the individual layers they radiate from the base of the deposit.

ORIGIN OF THE RECENT TUFAS.

Naturally the first hypothesis suggested when a Recent deposit is observed in the process of formation is that the solution from which it is separated is saturated with that particular substance. The solubility of calcium carbonate has been studied by many investigators¹ with somewhat varying results. In a preliminary paper² the results of Treadwell and Reuter, quoted by Seidell³ led to the belief that the present lakes in the Lahontan Basin were far from being saturated with calcium carbonate. In several recent papers Johnston and Williamson⁴ have shown that much of the previous work is misleading, and the following discussion is largely based on their conclusions.

The more important factors governing the solubility of calcium carbonate are the temperature of the solution, the amount of carbon dioxide in the air in contact with the solution, and the concentration of the other salts present in the solution. Of these the latter has the least importance and may for the present discussion be neglected.

In the papers just cited Johnston and Williamson quote the results obtained by Wells⁵ in a series of determinations of the solubility of calcium carbonate under different temperatures in pure water in contact with air containing 3.2 parts of carbon dioxide per 10,000. This is approximately the amount of carbon dioxide in the open air and in the absence of definite determination may be considered as representing actual conditions over the present lakes. The amounts of calcium carbonate found by Wells are given in the accompanying table.

Temp. °C.	CaCO ₃ parts per million.
0	81
5	75
10	70
15	65
20	60
25	56
30	52

The temperatures prevailing at various depths in Pyramid Lake were determined by sounding with a Sixes maximum and minimum thermometer at various localities in the lake during 1914, while at the same time the temperature of the surface film of water was determined with an ordinary chemical thermometer. The following table contains the data obtained.

The slight variation in the surface temperature was in part due to the different times of day at which temperatures were taken, the highest being obtained between 2 and 3 p. m. and the lowest early in the morning. The great variation in the temperature between the months of February and July is of course seasonal. As the highest temperatures observed were obtained at about the time of the maximum temperature of the lake, it is believed that 25° C. may be safely assumed to be the limit to which the water becomes heated. The corresponding amount of calcium carbonate which may remain in solution is 56 parts per million.

¹ For a summary of previous work, see Frank K. Cameron and James M. Bell, U. S. Dept. Agr., Bureau of Soils Bul. 49, pp. 36-57, 1907.

² J. C. Jones, *Geologic history of Lake Lahontan*, Science, vol. 40, pp. 827-830, 1914.

³ Atherton Seidell, *Solubility of inorganic and organic substances*, p. 87, 1907.

⁴ John Johnston, Jour. Am. Chem. Soc., vol. 37, p. 2001, 1915.

John Johnston and E. D. Williamson, Jour. Am. Chem. Soc., vol. 38, pp. 975-982, 1916.

John Johnston and E. D. Williamson, Jour. Geol., vol. 24, pp. 729-750, 1916.

⁵ R. C. Wells, Jour. Wash. Acad. Sci., vol. 5, p. 617, 1915.

Depth (feet).	Feb. 28, 1914, 2 ^h 35 ^m p. m., 300 yards off west shore opposite Anaho Isd.	Feb. 28, 1914, 4 p. m., 3 miles west of Anaho Isd.	Feb. 28, 1914, 5 p. m., half mile west of Anaho Isd.	July 14, 1914, 10 ^h 40 ^m a. m., 5 miles south of Needles.	July 15, 1914, 10 ^h 40 ^m a. m., near Needles.	July 20, 1914, 11 ^h 30 ^m a. m., a mile north of Pyramid Island.	July 21, 1914, 12 ^h 30 ^m p. m., near west shore 4 miles south of Sutcliff.
	° C.	° C.	° C.	° C.	° C.	° C.	° C.
Surface	7.0	6.8	6.1	22.8	20.4	21.4	21.0
5	6.6	6.6	6.1	20.8	20.0	21.6	21.1
10	6.6	6.6	6.1	20.5	19.3	21.2	20.8
15	6.6				19.3		20.5
25	6.1			20.1	19.0	21.1	20.5
50	6.1		5.8	19.4	16.0	19.2	20.5
75				11.4	13.0	11.7	16.1
100				9.7		8.3	
150				7.1		6.8	
200				6.2		6.0	
250							
300		5.5	5.5	5.6			
350						5.7	

ANALYSIS OF WATER OF PYRAMID LAKE.

In order that the following analyses of the water of Pyramid Lake may be compared, they have been recalculated to a common ionic basis and to parts per million.

Analysis.	1	2	3	4	5	6
Silica.....	Trace	42.5	41.2	2.0	4.0	Not det.
Iron, alumina.....				1.4	Trace	
Calcium.....	7.1		17.9	16.0	22.4	20.0
Magnesium.....	77.5	75.2	80.0	78.0	77.0	6.8
Sodium.....	899.9	1,182.6	1,173.1	1,251.0	} Not det.	28.6
Potassium.....	Trace	71.9	76.6	100.0		
CO ₂	32.7	494.0	499.8	160.0	172.8	
HCO ₃				681.0	956.2	88.6
SO ₄	156.0	177.2	180.3	183.0	196.2	21.4
Chlorine.....	1,387.0	1,428.8	1,439.8	1,455.0	1,470.0	13.0
Total solids ..	3,275.0	3,472.5	3,498.7	3,496.0	3,515.0	143.0

1. Sample collected 1867. O. D. Allen, analyst. King, U. S. Geol. Surv., 40th Par., vol. I, p. 528.
2. Sample collected 1882 near surface of lake 2 miles south of Anaho Island. F. W. Clarke, analyst. Russell, U. S. Geol. Surv. Monograph 11, p. 57.
3. Sample collected 1882 near surface 10 miles north of Anaho Island. F. W. Clarke, analyst. Russell, op. cit., p. 58.
4. Sample collected 1913 near surface 3 miles southwest of Anaho Island. M. B. Kennedy and Frank Banigan, analysts.
5. Sample collected 1914 near surface at north end of lake. Frank Banigan, analyst.
6. Mean of 10 composite samples taken 4 times daily from Truckee River near Derby, from April 10, 1906, to March 13, 1907. H. Stabler, U. S. Geol. Sur., Water Supply Paper No. 274, p. 127, 1911.

The Truckee River flows into Pyramid Lake at the southern end, and it will be noted that there is a slight increase in the salinity toward the northern end, where very little fresh water enters the lake. Owing to the thorough agitation of the lake waters by frequent winds, the difference in salinity of the two ends of the lake is not as great as might be expected.

Assuming, for the sake of argument, that all of the calcium present in the waters of Pyramid Lake is combined as calcium carbonate, the analyses would show the following amounts of CaCO_3 present at the times mentioned: 17.8 in 1867, 44.7 in 1882, 40.7 in 1913, 56.0 in 1914.

It will be observed that only the sample obtained at the northern end of the lake, in the vicinity of certain hot springs, to be described later, contained the required amount to saturate the water under the highest temperature attained. As this temperature is reached by the surface film only for a brief period during the days of the summer months, it seems quite unlikely that any considerable deposit could be formed. Granting that the surface-waters do become saturated and a deposit separates, it would seem that as it sinks to the cooler waters below, it would be redissolved and should show a higher concentration. The following analyses in parts per million obtained by Russell¹ show that this is not the case:

	South of Anaho Island.		North of Anaho Island.	
	1 foot below surface.	200 feet below surface.	1 foot below surface.	350 feet below surface.
Silica.....	42.5	30.0	41.2	20.0
Magnesium.....	75.2	82.3	80.0	80.5
Calcium.....			17.9	17.9
Sodium.....	1,182.6	1,180.9	1,173.1	1,181.7
Potassium.....	71.9	72.6	76.6	72.3
Chlorine.....	1,428.8	1,427.1	1,429.8	1,434.2
Sulphuric Acid.....	177.2	186.4	180.3	185.0
Carbonic Acid.....	494.0	509.8	499.8	492.1
(by difference)				
Total.....	3,472.5	3,490.0	3,498.7	3,483.7

Theoretically, as the lake waters are in continual contact with the calcium carbonate of the submerged tufa deposits, they should in time take enough into solution to approximate the limit of saturation. In addition, the streams and springs discharging into the lake are constantly bringing in further contributions of calcium. The Truckee River at present is adding some tens of thousands of tons of calcium yearly, as is shown by the analyses and discharge data² of recent years. As the lake waters are on the whole still somewhat below the limit of saturation for calcium carbonate, it is necessary to conclude that the substance is being removed rapidly enough to prevent its concentration. In this connection it is interesting to note that the relative amount of calcium in solution in the lake waters is somewhat less than in the waters of the inflowing Truckee River.

It must be admitted, however, that further chemical work is necessary before it can be definitely stated that the waters of Pyramid Lake are not saturated with calcium carbonate. The analyses available are too few and scattered, and while from our present knowledge it is thought that the influence of the accompanying salts in depressing the solubility of the calcium carbonate is slight, further work is necessary. At present it seems that only

¹ I. C. Russell, U. S. Geol. Surv. Monograph 11, pp. 57-58.

² U. S. Geol. Surv., Water Supply and Irrigation Paper No. 274, p. 127.

the surface waters at the northern end of the lake could possibly reach the saturation limit for brief periods during the warm summer days.

As calcium carbonate usually fails to separate from saturated solutions in the absence of the solid phase, it might be argued that the only deposit to be expected from the surface-waters would be found along the shores on the existing tufas. While the recent tufa often appears on the older tufas, in as many instances it is found on rocks that have no other calcareous deposits. In a far greater number of instances similar rocks exposed under identical conditions show no trace of the tufa, and any explanation of the deposit must show the cause of its erratic appearance.

The extreme local nature and constant association of the recent tufa deposits with the blue-green algæ indicate that they play some rôle in the precipitation of the calcium carbonate. The association of the algæ and calcium carbonate deposits¹ has been frequently noted in fresh-water lakes, streams, and springs elsewhere all over the world. In some manner, not well understood at present, the algæ are apparently able to cause the precipitation of calcium carbonate in their immediate vicinity. If the deposits were formed only from water saturated with calcium carbonate, it could be said that the algæ simply served to localize the tufas that would otherwise be more generally distributed. In Pyramid Lake, however, where only the surface films can possibly be saturated, the algæ grow best at depths of 3 to 10 feet and apparently deposit the tufa from cooler and unsaturated water.

Of the various suggestions accounting for their activity, only three need be considered. These are as follows:

(1) The action of certain bacteria² on calcium salts in solution through the formation of ammonia or ammonium carbonate. If bacteria are associated with the blue-green algæ responsible for the formation of the tufa, it is necessary to assume that the bacteria are active only in the presence of these particular genera of algæ, as no other group of algæ there present seems able to cause the deposition of calcium carbonate. In addition, the waters of Pyramid Lake were examined by Dr. Kellerman for the presence of the bacteria known to be active in the precipitation of calcium carbonate in the Atlantic Ocean and Great Salt Lake, with negative results.

(2) The formation of ammonium salts through the life process of animals reacting with calcium sulphate and causing the precipitation of calcium carbonate:³ In Pyramid Lake, however, the amount of calcium in solution is barely enough to approximately saturate the water with the carbonate and probably very little, if any, is deposited through the decomposition of the sulphate.

(3) The algæ are able to utilize the carbon dioxide in solution and so cause a local deficiency in their vicinity which in turn would lower the solubility of the calcium carbonate and cause a deposit to form about their filaments. Murray

¹ The blue-green algæ are known to be especially active in the precipitation of calcium carbonate, and there is an extensive literature, to which reference may be found in the following:

W. H. Weed, U. S. Geol. Surv., 9th Ann. Rept., pp. 619-681, 1889.

C. D. Walcott, Smithsonian Misc. Coll., vol. 64, No. 2, pp. 77-156, 1914.

H. Justin Roddy, Proc. Am. Phil. Soc., vol. 54, pp. 246-258, 1915.

T. C. Brown, Bull. Geol. Soc. Am., vol. 25, pp. 745-780, 1914.

Wayland Vaughan, Carnegie Inst. Wash. Pub. No. 182, pp. 1-78, 1914.

² Karl F. Kellerman and N. R. Smith, Jour. Wash. Acad. Sci., vol. 4, pp. 400-402, 1914.

³ Sir John Murray and Dr. Johan Hjort, *The depths of the Ocean*, pp. 177, 178, 1912.

and Hjort¹ consider this process as established, although, as far as known, no definite experimental evidence has been secured. This seems to be the more probable method by which the recent tufa has been formed at Pyramid Lake. Whether the algæ alone are responsible or are assisted by certain bacilli which may be associated with the algæ can not be stated. It can be said, however, that by whatever method the tufas are formed, the algæ certainly are the determining factor in the localizing and development of the tufa from the waters of Pyramid Lake.

OOOLITIC SANDS IN PYRAMID LAKE.

In addition to the recent tufa, calcium carbonate is being deposited at present in the form of oolitic sands in a very limited area near the northern end of the lake. The oolites occur along three small beaches at the eastern base of the highest of the tufa-covered pinnacles known as the Needles. At the head of the small bay occupied by the central oolite beach there is a group of feeble hot springs that discharge directly into the lake. As described by Russell² tubules of calcium carbonate have formed about the orifices of the springs. These are usually cylindrical, with an open passage-way through the center, and are aptly known as "fossil glove fingers." They vary in diameter from 0.5 to 3 inches and in height up to 6 inches. The larger ones are usually more irregular and are often capped by a mushroom-like mass with several orifices. The tubules are more or less arranged along small linear cracks in the older tufa that are sealed except where the tubules arise.

The flow from the individual orifices is very feeble, amounting to a gallon every 20 to 30 minutes, and probably the total visible flow is less than a gallon per minute. The temperature of the spring-water as measured at the different outlets varies from 48° to 63° C. Practically all of the flowing springs observed are submerged and discharge directly into the lake. While abandoned tubules may be observed to an elevation of 3 feet above the surface of the lake, the only one still flowing was a scant quarter of an inch above the present lake-level.

A thin section of one of the smaller tubules showed it to be made up of three layers. The medial layer was composed of a porous mass of crystalline granules 1 to 2 microns in diameter. These were usually compound and formed by the coalescence of two or more individual crystals with rude outlines, giving the granules a nodular appearance. Embedded in the mass of granules were numerous grains of sand and occasional diatom casts.

Both the inner and outer layers of the tubules were composed of prismatic crystals of aragonite elongated parallel to the prism and radiating from the surfaces of the medial layer. The crystals were densely packed, forming solid layers with but little foreign material included. The projecting ends of the crystals were capped by pyramids and, in the outer layer especially, fine zigzag lines ran through the mass parallel to the pyramidal faces of the individual crystals.

In the immediate vicinity of the orifices of the springs, the bottom of the lake is covered by a deposit of fine-grained, soft, creamy sands. Under the microscope these were found to be composed of loose granules identical in

¹ *The depths of the Ocean*, p. 177.

² U. S. Geol. Surv. Monograph 11, pp. 60, 61.

size and appearance with those forming the medial layer of the tubule. Somewhat farther away the granules became larger, with smoother surfaces, and were typical oolites. The oolites continued to increase in size for some distance from the springs, and occasional ones, 0.5 inch or more in diameter, could be found along the beaches. These larger individuals were seldom spherical, but were flattened on one or more sides.

Thin sections of the oolites disclosed their structure. They were built up of numerous concentric layers alternately clear and crystalline and fine-grained and stony. The clear crystalline layers were formed of minute crystals of aragonite about 10 microns in length, radiating outward from the surfaces of the stony layers. The stony layers were somewhat thinner and contained considerable sand.

The significance of the alteration is difficult to determine, but it is possible that the sandy and stony layers are deposited when the waters are agitated by storms and are somewhat roily, while the crystalline layers are the normal growth during periods of calm and clear water.

Nuclei of sand-grains and other foreign material are lacking for the most part, and the centers of growth of the oolites were chiefly masses of minute granules that were the first product of the saturated waters.

ORIGIN OF THE OOLITES.

A sample of the spring water was collected from the orifice that discharged a fraction of an inch above the level of the lake, by inserting a rubber tube and siphoning the water into a bottle. The water was analyzed by Mr. A. M. Jackson of the Nevada State Water Laboratory.

Analysis of water from Hot Springs at Needles (parts per million).

SiO ₂	147	HCO ₃	78
Fe.....	Trace.	SO ₄	255
Al.....	Trace.	Cl.....	2,693
Ca.....	272	B ₄ O ₇	None.
Mg.....	5	NO ₃	1
Na.....	1,312		
K.....	349	Total solids...	5,170
CO ₃	None.		

If it be assumed that all of the bicarbonate radical is combined with calcium, the water contains 104 parts of calcium bicarbonate per million and only 9 per cent of the calcium would be used. The lake-waters, on the other hand, contain abundant bicarbonates but very little calcium. An obvious conclusion is that the mingling of the calcium-bearing spring-water with the lake-water charged with carbonates results in the formation of far more calcium carbonate than is necessary to saturate the latter. Expressed quantitatively, it is necessary that 170 parts of the lake-water dilute 1 part of the spring-water at a temperature of 20° C. in order that no deposit may form as a result of the mingling of the waters. As the springs are located at the heads of small bays, the movement of the lake-waters in their vicinity is slight and it is not surprising that the deposits form. It is of interest to note that the sample of lake-water collected at this end of the lake and about a mile south of the springs contained the largest amount of calcium.

Vaughan¹ and his collaborators have shown that the oolitic muds forming at present on the Bahama Banks are being deposited largely through the activities of a certain bacterium, *Pseudomonas calcis*.² During 1914, samples of the water and muds in the vicinity of the oolitic deposits of Pyramid Lake were forwarded to Dr. Kellerman, who examined them for the presence of these bacteria. While none were found, several types of bacilli capable of growing in media of low salt concentration and under favorable conditions capable of causing a slight precipitation of calcium were present.

Studying the formation of the oolites forming at present in Great Salt Lake, Rothpletz³ concluded that algæ belonging to the genus *Glæocapsa* were responsible for the deposition of the oolites. Recent work by Kellerman has established the presence of a form almost identical with *Pseudomonas calcis* in Great Salt Lake in the vicinity of the oolitic deposits, indicating that the association of the *Glæocapsa* with the oolites is a fortuitous rather than a casual relation.

Glæocapsa are quite abundant in the northern end of Pyramid Lake, but are much more widespread than the local deposits of oolites. Away from the area of the hot springs, no evidence of the formation of oolites could be discovered in association with algæ.

In a recent discussion of the origin of oolites, Brown⁴ came to the conclusion that all oolites are formed from waters supersaturated with calcium carbonate. His arguments are largely based on the experimental evidence of Linck,⁵ who was able to produce oolites by adding either sodium or ammonium carbonates to sea-water. The following results of Linck's first experiment are strikingly similar to the observation of the oolites of Pyramid Lake. Adding sodium carbonate to an artificial sea-water and allowing the solution to stand 12 hours, he examined the precipitate under the microscope. The precipitate was crystalline and consisted essentially of minute spherulites, 0.02 mm. in diameter and smooth-surfaced as a rule, although those floating on the surface were rough with small radiating crystals. These gave an interference cross and one or two colored rings and were negative. In addition, there were numerous small aggregates of desmid-like crystals and bundles with negative elongation, together with columnar crystals apparently capped with domes. The spherulites were mostly perfect spheres, at times aggregated like *Globerina* and easily split through the middle by pressing on the cover-glass. All of the products gave the aragonite reaction with cobalt nitrate. Brown⁶ calls attention to the fact that all recent oolites are deposited as aragonite and the older oolites have been changed to calcite. The more recent work of Johnston, Merwin, and Williamson⁷ on the several forms of calcium carbonate clears up many of the puzzling questions involved in the precipitation of aragonite in saline solutions. There are four forms of calcium carbonate that may form from solutions: calcite, μ calcite, aragonite, and the hexahydrate

¹ T. W. Vaughan, Carnegie Inst. Wash., Pub. No. 182, pp. 1-78, 1914.

² Karl F. Kellerman and N. R. Smith, Jour. Wash. Acad. Sci., vol. 4, pp. 400-402, 1914.

³ Dr. A. Rothpletz, Bot. Centralblatt, vol. 35, 1892, translated by F. W. Cragin, Am. Geol., vol. 10, pp. 279-282, 1892.

⁴ Thomas Clacher Brown, Bull. Geol. Soc. Am., vol. 25, pp. 745-780, 1914.

⁵ G. Linck, Neues Jahr. Min. Geol. und Pal. Beil., Band 16, pp. 495-513, 1903.

⁶ Thomas Clacher Brown, Bull. Geol. Soc. Am., vol. 25, p. 750, 1914.

⁷ John Johnston, H. E. Merwin, and E. D. Williamson, Am. Jour. Science, 4th ser., vol. 41, pp. 473-512, 1916.

($\text{CaCO}_3 \cdot 6\text{H}_2\text{O}$.) Calcite is the stable form to which all the others revert, and is the general product of slow precipitation when in contact with aqueous solutions. At a pressure of one atmosphere aragonite is unstable at all ordinary temperatures, though it is possible that it may be stable at temperatures below -100°C . Aragonite is formed when precipitated from temperatures above 100°C ., or in the presence of a metal that yields an isomorphous carbonate such as lead carbonate. No other salts except calcium sulphate seem to have any specific effect. When aragonite was thus formed it contained a small amount of calcium sulphate apparently in solid solution. Aragonite was obtained by this method at temperatures as low as 19°C .

Once formed, aragonite is fairly stable. On shaking aragonite crystals in water at a temperature of 25°C ., it was only after 31 days that an appreciable change to calcite was noted. Aragonite crystals and water heated in a closed tube and allowed to stand for 2 years showed only a few rhombs of calcite on the walls of the tube. When dry, aragonite apparently persists indefinitely, owing to the slow rate of transformation. With increasing temperature the rate of transformation increases and at 470°C . takes place in a few minutes, the resulting calcite retaining the external form of the aragonite. In the presence of water, pure aragonite is apparently stable, but goes over into calcite very slowly, the rate again depending on the temperature and the presence of calcite crystals.

The μ calcite and hexahydrate form at lower temperatures but are very unstable, soon passing into calcite. As calcite is the most insoluble of the different forms, the precipitation of the unstable forms is believed to depend on the degree of supersaturation of the solution. In general, the latter depends on the mode of agitating the solution and the presence of other substances in solution. Where nuclei are present, no supersaturation should occur and the form of the precipitate is determined by the character of the nuclei. The size of the precipitated particles depends on the degree of supersaturation, the particles tending to be smaller and more numerous the greater the supersaturation. In one of their experiments¹ the momentary supersaturation was so great that a jelly resulted.

When the solution is saturated to the point where calcite should begin to separate, if no calcite nuclei are present the solution will become supersaturated with respect to calcite and reach the saturation point for aragonite. If still no nuclei are present, it will become saturated with respect to calcite and aragonite and may reach the saturation point of μ calcite when the precipitation of all three forms is possible.

In the laboratory it is difficult to distinguish between aragonite and μ calcite through chemical means alone, as both give the Meigan reaction with cobalt nitrate and it is necessary to resort to the microscope for their positive identification. As the oolites at Pyramid Lake have been proven to be aragonite by microscopic methods and μ calcite is so very unstable, it is unlikely that any of the calcium carbonate precipitated through the mingling of the spring and lake waters separates out as μ calcite, especially as the aragonite nuclei are present. In confirmation of the conclusion that aragonite forms at

¹ John Johnston, H. E. Merwin, and E. D. Williamson, *Am. Jour. Science*, 4th ser., vol. 41, p. 496, 1916.

low temperatures in the presence of sulphates, it is found that the oolites contain a small but appreciable amount of calcium sulphate.

From the close association of the oolites with the hot springs and the evident supersaturation of the lake-water in the immediate vicinity by the calcium carbonate formed by the reaction between the calcium-bearing spring-water with the carbonates of the lake-water, it is concluded that the oolites are forming through purely chemical means. The small granules, first formed as the two solutions mix, act as the nuclei around which the deposits continue to form from the saturated waters of the small bays.

Many of the oolites have become cemented, forming masses of oolitic limestone. Were the cementation a general feature, it would be suspected that this was simply another form of chemical deposit. The masses are quite sporadic in their occurrence and *in every case are associated with the blue-green algæ that are probably responsible for the formation of the Recent tufa.* Nowhere was there any evidence of the cementation of the oolites in the absence of the algæ discovered, and it was possible to confirm the hypothesis advanced for the origin of the Recent tufa under the most favorable conditions for a purely chemical hypothesis.

THE LAHONTAN TUFAS.

The tufas or calcareous deposits of Lake Lahontan are widely distributed throughout the lacustrine basin as isolated patches or sheets erratically distributed on the rock walls and gravels, or as isolated masses of fantastic shape simulating domes, columns, and crags. Almost without exception the deposits developed only on rock nuclei ranging in size from pebbles to the rock walls of the basin. In many instances where isolated pebbles formed the foundation, the tufa expanded in its upward growth, producing vase-like forms up to masses 1 and 2 feet in diameter. In the lower canyon of the Truckee River, near Pyramid Lake, these forms are so closely spaced that they form an almost continuous pavement near the top of the lacustrine clays.

In many instances the tufa enveloping the individual pebbles of the gravel-bars has cemented the gravels and formed firm foundations on which have been deposited continuous layers of tufa up to 3 feet in thickness. In other instances the growth of tufa on the gravels has been localized and columns and domes erected to a maximum height of 20 or more feet. Still more frequently the gravels have been simply cemented, forming thick layers of conglomerate.

In only two localities was the tufa found to have developed on sands or clays. In Astor Pass, to the south of the gravel-pit, a peculiar columnar form was noted that had grown on a sandy beach. This lies at the same elevation as the marl terrace that is found about the borders of Pyramid Lake and elsewhere about 150 feet above the present lake-level. The individual columns are about three-eighths of an inch in diameter and have an open canal running through the center. On closer examination it was found that the cores of the columns were composed of calcium carbonate deposited in and about the stems of *Chara* and reproducing the delicate structure of the plant with remarkable fidelity.

In the Smoke Creek Desert numerous instances were noted of pebble-like globular bits of tufa scattered over the surface of a broad terrace built up of

lacustrine clays and lying at about the present level of Pyramid Lake. This peculiar type of tufa had apparently formed in the absence of nuclei. In such sections of this terrace as were exposed it was found that the clay forming the upper 2 or 3 feet contained numerous more or less isolated crystals of thinolite tufa and that the globular tufa was for the most part attached to the crystals. As the latter are quite friable, it is possible that the loose globules found on the surface of the terraces had been broken from the thinolite. Whether the thinolite formed on the nodular tufa or vice versa could not be determined. There are certain algæ present in the muds of this locality that habitually form on the muds of shallow lakes and playas, but whether they form tufa or not is unknown at present. The Smoke Creek Desert, then, is the only locality in the Lahontan Basin in which any type of tufa has formed without a solid support.

In general, the tufas are yellowish gray in color, composed chiefly of granular calcite and varying in texture from solid, stony masses to open and porous coralline forms that often bear a striking resemblance to vegetative growth. Only a part of the tufas has outward crystalline forms. This particular type occurs as masses of elongate rectangular and rhombic crystals, sometimes solid but more frequently built up of nested plates or pyramids. As has been stated Russell¹ differentiated three types, calling the massive stony variety *lithoid*, the coralline *dendritic*, and the crystalline *thinolite*. As a matter of fact, there is a complete gradation from the lithoid to the dendritic type and from the dendritic into the thinolite.

The thinner films of tufa deposited directly on the rock walls of the basin and usually forming the cores of the tufa domes and crags are massive and banded, and on close examination are seen to be made up of a multitude of small protuberant individuals radiating from the base, similar to the films of recent tufa already described.

When the tufa layers are 1 to 6 inches in thickness, the exposed surface is rough and hackly from the projecting points of the individual columns and plates forming the mass. When the deposits of tufa are thicker the component plates and columns become larger, tend to separate, and eventually the mass becomes coralline and of the dendritic type. As a result it is impossible to draw sharply the line between the lithoid and dendritic tufas and say where one ends and the other begins. Frequently in the thicker masses the upper surfaces of the projecting layers of tufa will be coralline and dendritic, while the lower surfaces will be stony and lithoidal. This would seem to indicate that the same relations that were true in the older tufas of the Salton Basin were true in the Lahontan Basin and that the dendritic type forms where conditions of growth were favorable, while the lithoid tufa is deposited in the darker and more unfavorable situations.

While there is some gradation between the dendritic type and the thinolite, the transition is quite abrupt and the thinolite is more nearly a distinct type. The thinolite tufa is best developed in the Pyramid and Winnemucca Lake Basins, although it is found in the Smoke Creek and Black Rock Deserts and in the Carson Sink. In the first four basins mentioned it begins, at an elevation of 145 feet above the present level of Pyramid Lake, as a narrow layer of small crystals intercalated between a 2-inch layer of lithoidal tufa at the

¹ U. S. Geol. Surv. Monograph 11, pp. 188-203.

base and a 3 to 6 foot zone of more coralline and dendritic tufa above (fig. 13). At lower elevations it rapidly increases both in thickness and in the size of the crystals. At the level of a well-developed terrace, about 110 feet above the lake-level and called the Thinolite Terrace by Russell, it forms a layer nearly 4 feet in thickness. At the edge of this terrace, on the southwest corner of Anaho Island in Pyramid Lake, a very good typical section is exposed, as is shown by figures 14 and 15. Here the base of the tufa deposit is composed of 10 inches of dense lithoidal tufa showing a mammillary structure on the exposed upper surfaces. On this is a 24-inch zone of open reticulated thinolite crystals, composed of many large crystals 6 to 8 inches in length and projecting at right angles to the base. These have a multitude of smaller crystals attached and radiating in all directions. Toward the top the confused mass becomes more compact and rapidly passes into a 20-inch zone of parallel crystals 6 or 7 inches long, solidly packed and divided into three equally spaced layers by two narrow lines of small crystals radiating in all directions from the larger crystals. This zone in turn passes into a 6 to 12 inch layer of rather compact dendritic tufa that is largely columnar and simulates to some extent the appearance of the thinolite. This grades into a more lithoidal tufa with a decided mammillary structure. The section exposed is 8 feet in thickness. At the water-level the thinolite layer is about 5 feet in thickness, having gradually thickened below the thinolite terrace.

In the Carson Sink the thinolite is but slightly developed and occurs as a 2 to 4 inch layer near the bottom of the tufa deposits. On Rattlesnake Hill, near Fallon, its upper limit is approximately the present level of the thinolite terrace, or about 35 feet below the elevation of the upper limit of the thinolite in the other basins mentioned.

While it is true that the different types of tufa are dominant in the zones recognized by Russell¹ yet they are mingled and grade into one another far more than he had supposed. From their intimate admixture there is no doubt that two and possibly all three of the forms of tufa could form simultaneously. The progressive change from the higher elevations to the lower limit still available to observation is much more striking and significant than the variation in character at any given level.

The change in character with elevation (fig. 2.) is especially well displayed on Anaho Island. The island rises nearly 520 feet above the lake, and its highest point is but 10 feet below the highest level reached by Lake Lahontan. The tufa begins at the summit, filling the wider cracks of the rocks, and in isolated patches it is 6 inches thick on exposed surfaces. By far the greater part of the rock surface is bare, and no evidence could be found that suggested that it had ever been completely covered.

At a somewhat lower elevation on the northern slope of the island the tufa covers the face of a cliff as a continuous layer 1 to 2 feet in thickness, composed of pendant plates that produce a remarkable illusion of an immense draped tapestry of stone (fig. 16). At 350 feet above the lake the lower ends of the plates begin to turn out at an angle of 45°. Still lower the plates become longer and at their outer edges turn toward the horizontal, forming a mass of slightly drooping layers or shelves projecting 10 to 15 feet from the original rock-surface. The upper layers of the shelves are formed of compact lithoidal

¹ U. S. Geol. Surv. Monograph 11, p. 203.

tufa from which hangs a multitude of pendant columns and plates of dendritic tufa. These turn toward the outer edge of the deposit and at the edge frequently turn upward forming small shallow basins (fig. 19).

About 150 feet above the lake, or 40 feet above the thinolite terrace, the thickness of the tufa rapidly decreases and the sea face of the terrace has only a few isolated patches of tufa about a foot in thickness. At the southwest corner of the island a mass of tufa developed at the outer edge of the sea-face of the thinolite terrace and was afterwards broken so that it displays a complete section (see fig. 17) from the rock-surface outward.

From the level of the thinolite terrace to the water's edge the tufa deposits are similar in structure and thickness to the section described on page 20. Russell limited the thinolite to the area between the thinolite terrace and the present water-surface, stating¹ that at only one point did he find it above the

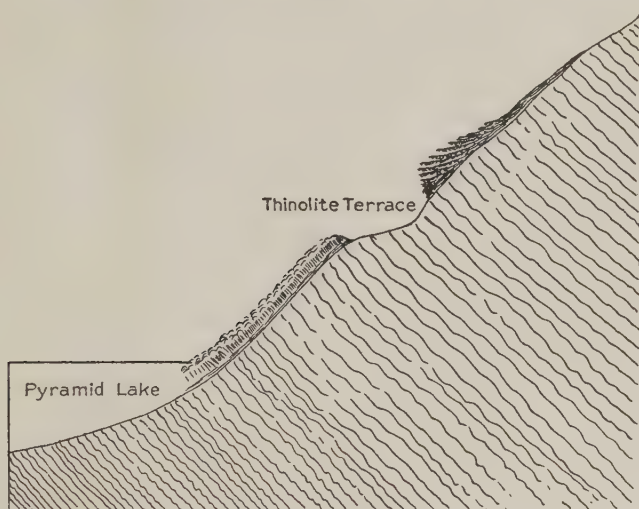


FIG. 2.—Diagram illustrating the vertical variation in the Lahontan tufas.

terrace. In reality, however, the thinolite layer extends some 30 feet above the terrace, gradually decreasing in thickness until it ends in a 2-inch layer of small crystals included in the base of the dendritic tufa and separated from the rock-surface by a 2-inch layer of lithoid tufa.

Thin sections of the different varieties of tufa disclosed numerous fragments of algæ in the lithoid and dendritic types. In figure 18 they may be seen as short, dark threads radiating from the base of the deposit. Numerous shells of gastropods are included in the dendritic tufa, more abundantly distributed on the under sides of the projecting shelves. Between 150 and 190 feet above the present lake a zone 1 foot thick and tapering both above and below, of cemented casts of *Chara*, lies at the base of the tufa (fig. 20). This is at the same elevation as the marl terrace described by Russell², and, as will be shown later, the marl is composed of similar material.

¹ I. C. Russell, U. S. Geol. Surv. Monograph 11, p. 194.

² I. C. Russell, U. S. Geol. Surv. Monograph 11, pp. 149-153.

At the Marble Buttes, a low range of hills composed of Triassic limestone, lying at the southern end of Pyramid Lake, the tufa extends over a greater proportion of the surface than at Anaho Island. On the southern face it is largely confined to two bands, the lower and weaker extending for 30 feet from the edge of the thinolite terrace, and the second at an elevation of 275 feet above the present lake. The upper band has a tendency to grow out at an angle from the rocks, but does not show the "shelf" structure as much as the tufa on the island. On the northern face of the buttes the tufa forms a more nearly continuous sheathing. At the top at the high-water mark it begins as a half-inch film that is exceedingly difficult to distinguish from the calcium-carbonate coating of the limestone formed by the weathering agencies. Within 10 feet of the high-water mark the tufa is 4 to 6 inches thick and rapidly increases in thickness as the cliff is descended. As on the island, it hangs in pendants which begin to turn out from the cliff 100 feet lower. About 200 feet above the lake the outer edges are horizontal, and the shelf-like projections extend 20 feet from the face of the supporting rocks. When within 50 to 25 feet of the thinolite terrace the tufa abruptly ceases and only a few thin patches can be found until the terrace is reached. Below the terrace the tufa begins again as a thin film, gradually increasing in thickness until at the base of the buttes the combined thickness of the tufas is 10 feet.

The Needles are a group of tufa-covered hills at the northern end of Pyramid Lake. The highest stands 300 feet above the lake, and while the majority of them undoubtedly have rock cores, yet the deposit of tufa so completely masks them that seldom are the underlying rocks seen. At the eastern base of the highest point are located the hot springs already described and the beaches covered with oolitic sands. All of the older tufa is much more compact and solid than at the island, while the recent tufa is soft and spongy. As at the island, the thinolite extends 38 feet above the thinolite terrace.

Pyramid Island is similarly completely covered with tufa, but on the northern side much of it has broken off, disclosing the underlying rock.

Elsewhere in the Pyramid Lake Basin, the tufa deposited on the rocks occurs in decidedly sporadic and isolated patches. There is a decided tendency to form bands at the outer edges of the terraces, as noted on the southern side of the Marble Buttes, but nowhere is there even a suggestion of a continuous coating extending from the high-water mark to below the surface of the present lake, with the possible exception of the Needles and Pyramid Island. Aside from the Pyramid and Winnemucca Lake Basins the tufa deposits are less numerous and are decidedly thinner. While thicknesses of 10 feet are not uncommon in the basins mentioned, it is rare to find deposits over 3 feet in thickness elsewhere. The tufa in the Carson Sink and Walker Lake Basin is more lithoidal and has a somewhat different aspect than that in the Pyramid Lake Basin. Near Hazen the tufa has formed on the surface of a long gravel-bar in small, convoluted plate-like masses that resemble very closely the plant commonly known as "hen and chickens."

In addition to the tufa clinging to the rock-walls of the basin, many deposits occur as isolated masses of fantastic form which were designated by Russell¹ as tufa domes, castles, towers, crags, etc. For the most part these occur at elevations below the thinolite terrace, and wherever their bases may

¹ U. S. Geol. Surv. Monograph 11, pp. 207-210.

be observed are standing on a solid basement of rock or cemented gravels. In every instance the character of the tufa forming these masses corresponds in detail with the tufa deposited at the same elevation on the faces of the cliffs.

In many instances the tufa towers are cylindrical (fig. 21) with a diameter of 20 feet and reaching heights of 30 to 40 feet above their bases. From the rough similarity in outline to the miniature towers or tubules forming about the mouths of the hot springs, Russell¹ believed they were of similar origin. This hypothesis was apparently supported by the tufa columns submerged in Mono Lake, from which cold fresh-water springs are issuing. The only suggestion that the towers at one time possessed conduits for the passage of spring-waters is the shallow depressions found at the top of some, produced by the weathering of the tufa. In no instance where the towers had been broken so as to disclose their interior was any suggestion of a passageway to be found. As the tufa in these isolated masses is entirely like the tufa found elsewhere, it is concluded that they have a similar origin.

ORIGIN OF THE LAHONTAN TUFAS.

The origin of the different types of Lahontan tufas remains to be discussed. Any purely chemical hypothesis advanced is difficult to harmonize with the exceedingly sporadic occurrence of the tufa masses. In many places, as at the Marble Buttes, the bare rock-face is exposed within a fraction of an inch of a tufa deposit several feet in thickness. While many of the gravel bars are more or less cemented, there are no cemented sands or beds of calcareous muds aside from the marl developed in former sheltered bays and limited to a narrow terrace 150 feet above Pyramid Lake.

A purely physical hypothesis advanced by Gilbert² in his study of Lake Bonneville, explaining the formation of the tufa through the expulsion of carbon dioxide by the action of the waves striking on the rocks of the shores, fails to account for the erratic occurrence of the deposits. Bare rock-surfaces and cliffs fully exposed to the action of the waves are far more numerous than those bearing tufa deposits. This is especially well shown along the eastern shore of Pyramid Lake, to the north of Pyramid Island, where some 10 miles of bare rock that were fully exposed to the action of the waves bear practically no tufa whatever.

The presence of the remains of the algæ in the dendritic and lithoid tufas, the tendency of the tufas to develop toward the light, the abundance of snails and other animal life associated with the tufas implying a food-supply furnished by the algæ, and the origin of the tufas forming at present through the activities of the algæ, lead to the conclusion that the dendritic and lithoid tufas of Lake Lahontan had a similar origin. The erratic occurrence of the tufa deposits is then easily explained, for they would form only where the algæ became established.

ORIGIN OF THE THINOLITE TUFA.

The origin of the thinolite has long been an unsolved problem. In an earlier study of the crystals, Dana³ believed them to be tetragonal and sug-

¹ U. S. Geol. Surv. Monograph 11, p. 222.

² G. K. Gilbert, U. S. Geol. Surv. Mon., vol. 1, p. 168, 1890.

³ E. S. Dana, U. S. Geol. Surv. Bull. No. 12, 1884.

gested that they might be pseudomorphs of a chlor-carbonate of calcium, a mineral unknown to occur in nature. It must be remembered that the thinolite crystals are frequently merely a mass of thin plates and cavernous, especially when they exceed an inch in length. The larger crystals are predominantly square or rectangular in cross-section, with a decided tendency to have the corners developed beyond the faces, so that they have a ribbed appearance. This is well shown in the cross-section (fig. 3, *g*) of one of the larger crystals. Usually the crystals terminate in a point when square in cross-section, but end in a ridge when rectangular.

The smaller crystals, however, are dominantly rhombic in cross-section (fig. 3, *d* and *o*) and are more perfectly developed. They usually occur as double rhombic pyramids, as in figure 3, *a*, *c*, *m*, and *n*. They display the symmetry of the normal class of the orthorhombic system.

An attempt was made to measure the angles of the more perfect crystals with a contact goniometer. As the faces were more or less imperfect and roughened by protuberant growths, no great amount of accuracy could be obtained. The angles between the prism-faces on the crystals with rhombic cross-sections approximated 63° and the angles measured over the apices of the brachydome approximated 31° , which would give an axial ratio of 0.6128 : 1 : 3.6059. Knowing that the recent tufa was being deposited in the form of aragonite, the values obtained were compared with the axial ratio of that mineral, 0.622444 : 1 : 0.720560, and it was noted that while the value for *a* was rather close, the value for *c* was 5.0043 times as great. From this close correspondence with the axial ratio of aragonite it was concluded that the original mineral was aragonite and the brachydome was the 051 form. Measuring the angles on the other forms present, it was found that the macrodome was 301 and the pyramids 221 and 441. On some of the crystals a trace of the basal pinacoid, 001, was observed and, while other forms aside from those mentioned may be present, no very definite evidence of their occurrence could be noted.

The cause of the tetragonal appearance of the crystals with square cross-section was now apparent, for the angles of the domes are such as would cause them to meet at a point when, as was usually the case, the crystals grew at the same rate along both horizontal axes.

Having decided that the original mineral forming the thinolite was aragonite, the experiment was tried of adding a saturated solution of calcium carbonate to a sample of the Pyramid Lake water and allowing it to stand several days. A deposit formed on the bottom of the flask, and on examining it under a microscope it was found to be composed of minute double pyramids of aragonite quite similar to the smaller crystals of thinolite.

It would seem, therefore, that the thinolite was formed at a time when Lake Lahontan became practically saturated with calcium carbonate. Nevertheless, the thinolite was never deposited, except where there was preexistent tufa to serve as a nucleus. The scattered crystals found in the clays of the broad terraces of the Smoke Creek Desert seems to be an exception, however, and while it is possible that they were deposited on small nodules of tufa formed by algæ growing on the muds, yet they may have separated spontaneously from the lake-water and fallen to the bottom.

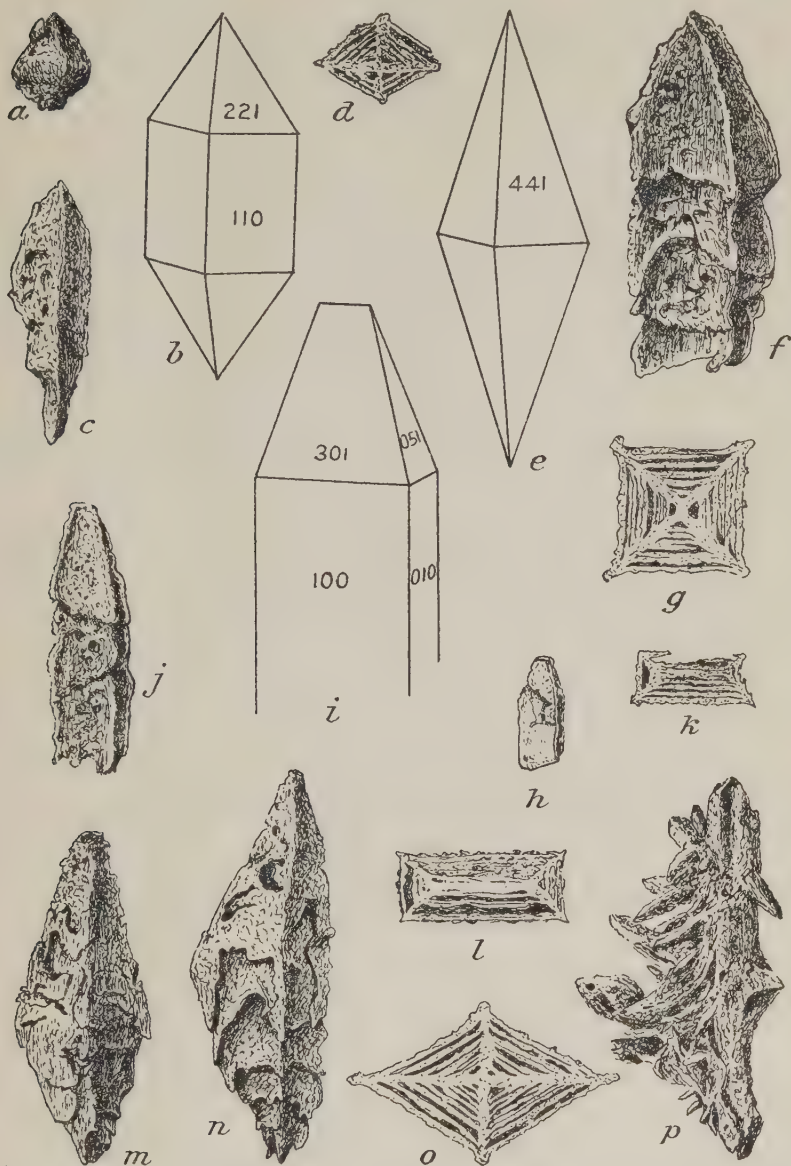


FIG. 3.—Crystals of Thinolite Tufa.

a. Small double pyramid and prism.

b. Crystal forms occurring on a.

c. Double pyramid and prism.

d. Cross-section of c.

e. Pyramid occurring on c.

f. Domes and pinacoids as in i.

g. Cross-section of f.

h. Domes and pinacoids.

i. Crystal forms occurring on f, h, and j.

j. Domes and pinacoids.

k. Cross-section of j.

l. Cross-section of h. x 4.

m and n. Double pyramids.

o. Cross-section of m.

p. Intergrowth of crystals.

In accord with the laws of crystallization, we thus have positive evidence that at no time did the water of Lake Lahontan, with the possible exception of Smoke Creek Desert, become supersaturated to the point of spontaneous crystallization. As the concentration increased to the limit of solution the surplus was deposited on the tufa or solid phase with which the solution was in contact.

ORIGIN OF THE CHARA MARL.

As described by Russell,¹ the marl formed in Lake Lahontan is found in sheltered bays about the deeper portions of the old lake at approximately the same elevation throughout the basin. It usually forms a low terrace between 150 and 190 feet above the present lake, and its striking white outcrop may be seen for many miles. During the construction of a branch of the Southern Pacific Railroad a shallow cut was excavated through the marl in Astor Pass near the northern end of Pyramid Lake, and the marl was found to be composed of a mass of hollow tubes 0.25 to 0.5 inch in length and 0.04 inch in diameter. Snail-shells were especially abundant, and the marl at the surface was evidently produced from the disintegration by the weathering of the tubes and shells.

On closer examination of the tubes under a lens, it was found that the cross-section is a perfect reproduction of the cross-section of the stems of *Chara*, an alga that is still growing at depths of 18 to 20 feet in the present lake. Davis² has demonstrated the origin of marl through the activity of *Chara* and the present occurrence is a striking corroboration of his conclusions.

RELATION OF TUFAS TO THE HISTORY OF LAKE LAHONTAN.

In the light of a better understanding of the origin of the calcareous deposits of Lake Lahontan, it is possible to indicate their bearing on its history. As the formation of tufa could have begun as the basin first began to fill and has continued to the present, there is no necessity to infer a period of complete desiccation or of high salinity at any time during the existence of the lake. The further evidence must be sought in the elastic sediments and other lacustrine records.

It is possible to determine whether Pyramid Lake is a remnant of Lahontan by comparing the actual amount of tufa deposited with the amount that should have been deposited if the calcium has been brought into the lake in the same relative amount as at present in comparison with the combined sodium and potassium.

One reading the reports of King and Russell is apt to gain the impression that the deposits of tufa form a more or less continuous sheathing of the rock walls of this basin. This is not the case, however, as a liberal estimate of the areas of the basins of Pyramid and Winnemucca Lakes covered with tufa is 1 per cent. Elsewhere in the Lahontan Basin the tufa-covered areas are much less abundant. The average thickness of the tufa above the thinolite terrace is approximately 3 feet, and below the terrace about 8 feet. The area of the basin containing the Pyramid and Winnemucca Lakes was determined by a planimeter from the topographic sheets. Combining the estimates of area,

¹ U. S. Geol. Surv. Monograph 11, pp. 149-153.

² C. A. Davis, Jour. Geol., vol. 8, pp. 495-497, 1900.

thickness, and specific gravity, it was calculated that about 65,000,000 tons of tufa had been deposited.

Obtaining the volume of the lakes by measurement of the areas of the subaqueous contours on the maps published by Russell, the total amount of sodium and potassium contained in the present lakes was obtained. The present ratio between the sodium-potassium and the calcium is 1 to 0.007 in Pyramid Lake, 0.014 in Winnemucca Lake, and 0.6385 in the Truckee River. On this basis 99,000,000 tons of calcium carbonate have been deposited from the waters at present in the lakes.

It must be admitted that there are many factors that might materially affect the results and that the estimates are but a rough approximation. While the Truckee River is the only large stream that enters the lakes, yet a considerable amount of water discharges from other small streams and

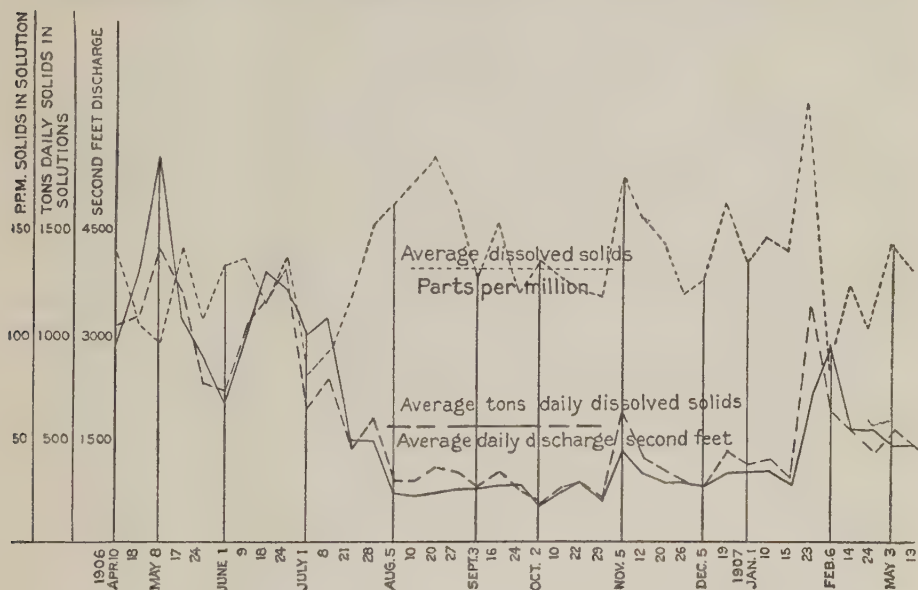


FIG. 4.—Analyses of daily samples of Truckee River from April 10, 1906, to May 13, 1907. Note relation between the amount of dissolved salts and the volume of water. Data from the U. S. G. S. Water Supply Paper No. 274.

springs. It is possible that the ratio between the alkalis and calcium changed somewhat during the more humid period that made the greater lake possible. The concentration of the waters may have been different, although such data as are available concerning the present streams indicate that there is little difference between periods of flood and low water. For example, the results of the analyses of daily samples taken from the Truckee River during 1906-7 by the United States Geological Survey¹ make it possible to approximate the effect of this factor (fig. 4). The ratio of the sodium-potassium to the calcium during the flood period is 1 : 669, and during the period of low water is 1 : 562, or an increase of 16 per cent in the relative amounts of calcium during the period of abundant flow. In turn, the relative amount of dissolved salts

¹ Herman Stabler, U. S. Geol. Sur., Water Supply Paper No. 274, pp. 273-275, 1911.

carried decreased 22 per cent during the period of flood. The amount of water carried during the flood period is 242 per cent greater than the amount passing during the period of low water. As will be shown later, it is believed that the actual increase in the mean flow of the Truckee River during the existence of Lake Lahontan was but 100 per cent. The effect of the increased flow, therefore, would not materially affect the conclusion drawn from such data as are at hand. In consequence, it is thought that the approximate correspondence between the amount of tufa deposited and the amount that should have been formed to leave the present amount of salts in the lakes in question indicates that Lake Lahontan has never been completely desiccated and that Pyramid and Winnemucca Lakes are two of the several residuals of the older and larger lake.

In a study of the fishes of the Lahontan Basin, Snyder¹ came to the same conclusion, and the harmony between the biological and chemical evidence greatly increases the probability that the conclusion is correct.

DURATION OF LAKE LAHONTAN.

If the present lakes are remnants of Lahontan it is possible to approximate the length of the period that compasses its history. Knowing the amount of salts at present in the lakes and determining the rate at which the present streams are carrying salts into the lakes, the number of years that have elapsed since the basin first began to fill may be calculated.

Of the present lakes in the Lahontan Basin the Black Rock and Smoke Creek Basins are playas; Carson, Humboldt, and Honey Lakes have been known to go dry, while Pyramid, Winnemucca, and Walker Lakes are permanent. The playas and temporary lakes furnish inadequate data for the determination of the age of Lake Lahontan as there is a certain possibility of the loss of some of the salts through burial and by absorption by the muds. Only the permanent lakes can be used as the least likely to have lost any considerable portion of their salines. As will be shown later, each basin was self-sustaining during the more humid periods and there has been little or no transfer of salts from one basin to another. Consequently the rate at which the present drainage of the permanent lake basins is adding salts to the lakes can be used as an indication of the length of time that has elapsed since the lakes first began to form.

Using the detailed map² of Pyramid and Winnemucca Lakes, it is possible to obtain the volumes of the lakes by determining the areas of the sub-lacustrine contours by means of a planimeter and calculating the volumes of the respective sections. Such a determination indicated the amount of water present in Pyramid Lake as 7.787 cubic miles and 1.142 cubic miles in Winnemucca Lake. The Truckee River has an average flow based on measurements³ at Vista, a station in the Truckee Canyon below all of the larger tributaries, made during the years 1899 to 1911, inclusive, of 0.274 cubic mile per year. It would take the Truckee River 28.42 years to supply the water at present in Pyramid Lake and 4.17 years additional to fill Winnemucca Lake. But Pyramid Lake contains 1,455 parts per million chlorine, Winnemucca

¹ John Otterbein Snyder, Jour. Wash. Acad. Sci., vol. 4, pp. 299-300, 1914.

² I. C. Russell, U. S. Geol. Surv. Monograph 11, plate 9, p. 56.

³ U. S. Geol. Sur., Water Supply Paper No. 300, pp. 106-108.

Lake 2,184 parts per million, and the Truckee only 13 parts per million. Pyramid Lake, then, contains 111.9 times and Winnemucca Lake 168 times as much chlorine as the Truckee River. It would therefore take the Truckee 3,180.2 years to supply the chlorine in Pyramid Lake and 700.56 years additional to furnish that of Winnemucca Lake, or 3,880.8 years for both. A similar calculation, using sodium instead of chlorine, gave 2,447 years necessary and the other substances gave still lower results. Of these calculations the first is probably more nearly the truth, as chlorine is the least likely to be removed from solution. No great degree of accuracy can be claimed, for many factors may have influenced the result. While the Truckee River is the only stream of considerable volume that flows into the lakes, yet a considerable amount of water is supplied by the intermittent streams and springs about the borders. Further, a considerable amount of water is diverted by irrigation from the Truckee both above and below the gaging station, and the actual flow into the lakes at present is somewhat less than the volume used in the calculations.

The amount of salts carried probably varied somewhat with the increase in flow of the river during Lahontan times, although, as has been shown, the present data indicate no very great change. Of the factors mentioned only one, the last, would tend to make the period greater, while the others would cause the actual period to be less than the calculated duration of Lake Lahontan.

The question may be approached from an entirely different angle. As it happened in 1913, the level of Pyramid Lake was but 5 inches below the level at the time of Russell's visit. A sample was collected near the locality where he obtained his southern sample and the chlorine determined. The gain during the 31 years that had elapsed between the two visits was 23 parts per million. As the lake had essentially the same volume in both instances and the samples were taken at the same locality, the variable factors are eliminated as far as possible. Dividing the total chlorine found in 1913 by the gain and multiplying the result by 31, the years that had elapsed, gave 1,956 years as the time necessary for the chlorine to accumulate, providing the present conditions had not been materially changed.

This method is open to the criticism that it depends on but two analyses, and while it is of value as corroborative evidence, yet it can not be considered as conclusive.

Still another method, one used by Russell,¹ may be employed. Knowing the total amount of chlorine in the two lakes and the rate of evaporation, the length of time necessary to evaporate enough water to supply the chlorine may be determined. Using the recent analyses, Pyramid Lake contains 1,440 parts per million of chlorine. Assuming that the water carried into the lake was as fresh as in the Truckee River, the water before evaporation contained 13 parts per million of chlorine. This would make it necessary to evaporate 111 cubic miles of river water to concentrate 1 cubic mile of Pyramid Lake water, or, since the lake contains 7.787 cubic miles, 864.36 cubic miles have been evaporated since the beginning of Pyramid Lake. Similarly, 180.43 cubic miles additional would be required to furnish chlorine in Winnemucca Lake.

¹ I. C. Russell, U. S. Geol. Surv. Monograph 11, p. 227.

The actual amount of evaporation from the lake-surfaces in Nevada has never been accurately determined. As a result of a series of observations made near Reno during 1907, Bigelow¹ came to the conclusion that a lake-surface evaporates about five-eighths as fast as an isolated pan placed outside the vapor blanket overlying the lake. The principal factors involved seemed to be the surface temperature of the water, the relative humidity of the air immediately over the lake, and the rapidity with which this air was removed by the wind. In large lakes the last factor is practically negligible, as the vapor blanket is simply moved about by the wind over the surface of the lake.

Records obtained by Peterson² for the summer of 1912 near Lovelock are of interest. Two similar pans 29 inches square were exposed, one on land and the other floating on the Humboldt River. The records for the pan on land are complete, but 5 days in June and 19 days in July are missing from the records of the floating pan. As the average evaporation of the previous and succeeding months was 77 per cent of the evaporation on land, this percentage of the land evaporation has been interpolated to complete the record.

Month.	Evaporation on land.	Evaporation on river.	P. ct.
May 12-31 (inc.)..	4.25	2.68	63
June.....	8.18	6.22	76
July.....	6.94	6.23	89
Aug.....	6.57	5.04	77
Sept.....	3.56	2.74	77
Oct. 1-26 (inc.)...	2.47	1.64	66
Total.....	33.97	24.55	Av. 72

The ratio between the river and land pans is probably somewhat too large, as the river-surface exposed is very small as compared with the lake-surfaces and evaporation greater from the river than from the lakes.

Observations conducted by the U. S. Reclamation Service near Fallon during the years 1908 to 1914 indicated a mean annual evaporation of 65.14 inches from an open pan on land. This is checked by the results of Peterson for the year 1912, where a pan exposed near Reno evaporated 64.28 inches. If we assume the ratio suggested by Bigelow as being approximately correct, an annual evaporation from the lakes of the Lahontan Basin of 40.71 inches would be indicated. If we consider the ratio established between the two pans exposed near Lovelock as correct, this would indicate 46.18 inches annual evaporation from the lakes.

At Lake Tahoe, which the Truckee River drains, Duryea³ found a mean annual evaporation from a pan floating in the lake to be 30.51 inches in a series of observations extending from 1900 to 1906. Lake Tahoe, however, is about 2,300 feet higher than the present lakes in the Lahontan Basin, and evaporation is less at its elevation.

The Salton Sea has fallen an average of 55.6 inches annually for the past few years,⁴ and as the amount of inflow and rainfall is slight, this may be considered as a close approximation to the annual evaporation.

¹ F. H. Bigelow, Monthly Weather Review, Feb. 1908, p. 22.

² F. L. Peterson, State Eng. Rept., 1911-12, pp. 179-181, 1913.

³ Edwin Duryea jr., Eng. News., Feb. 29, 1912. Also quoted U. S. Geol. Surv., Water Supply Paper No. 30, pp. 78-80.

⁴ U. S. Geol. Surv., Water Supply Paper No. 30, p. 410.

A rough estimate may be had from the annual inflow of the Truckee into Pyramid and Winnemucca Lakes. Neglecting the amount of water withdrawn from the streams below the gaging station by evaporation and for irrigation as being approximately balanced by the inflow from springs and minor streams, as well as the rainfall on the lakes, an annual evaporation of 52 inches is indicated.

In the absence of accurate determination it is believed that an assumption of 50 inches annual evaporation from the lakes under present conditions will not be far from the truth. Under the moister climate of the period of the expanded lake this would be undoubtedly diminished. A suggestion was obtained by comparing the evaporation of Lake Tahoe¹ with the rainfall at Truckee month by month, and it was found that the average evaporation for the wet years was 80 per cent of the average evaporation during the dry years.

The average area of Pyramid and Winnemucca Lakes during the Lahontan period is difficult to estimate, but it is believed that the area at the level of the thinolite terrace is approximately correct. The lakes are situated in deep, flat-bottomed valleys, and the greatest amount of variation in area would occur during the first 200 feet of rise. As the thinolite terrace is 110 feet above the present lake-level, this would give a fair mean of the area of lake-surface during its fluctuations. The area of the two lake basins at the level of the thinolite terrace is approximately 550 square miles. An evaporation of 50 inches annually would cause a loss of 0.4345 cubic mile each year. Since a total of 1,044.77 cubic miles have evaporated to concentrate the amount of chlorine at present in the two lakes, this would take 2,400 years in round numbers. If we assume the present area of the lakes as the unit surface of evaporation, the period would be 4,300 years. The difficulty in determining the actual average area involved makes this method somewhat uncertain, but the true period of years that has elapsed since the beginning of Lahontan probably lies between the limits named.

While none of the methods used can be considered as accurate, mainly on account of insufficient data, yet it may be safely assumed that the results indicate the approximate age of Lake Lahontan, provided no large amount of the salts has been carried out of the basins of the lakes considered by overflow to other portions of the Lahontan Basin.

In discussing a former paper² in which the broader conclusions of the study were given, Gale³ suggested that a considerable amount of the salts had been washed out of the Pyramid Lake Basin by overflow to the Smoke Creek and Black Rock Basins to the north.⁴ This possibility had been considered previously, but from such data as were available it seemed that the drainage and rainfall of these basins were sufficient to maintain these arms of Lake Lahontan independently and that there had been but little transfer from the different basins.

¹ Edwin Duryea jr., Eng. News, Feb. 29, 1912.

² J. C. Jones, Science, n. s., vol. 40, pp. 827-830, 1914.

³ H. S. Gale, Science, n. s., vol. 41, pp. 209-211, 1915.

⁴ A subsequent extensive drilling campaign in the Smoke Creek and Black Rock Basins failed to find any salt deposits in the lacustrine sediments that could be considered as indicating an extensive overflow from the Pyramid Lake Basin.

RAINFALL IN THE LAHONTAN BASIN.¹

The more striking features of the annual rainfall in the Lahontan Basin are its concentration in the cooler part of the year and its intimate relation to the mountain ranges. More than one-half the total annual rainfall comes during the months December to March, and over three-fourths during the 7 months from November to May. This is well illustrated by the records of the following stations, chosen as typical of all parts of the basin:

Month.	Susanville.	Truckee.	Reno.	Winnemucca.	Elko.
	<i>inches.</i>	<i>inches.</i>	<i>inches.</i>	<i>inches.</i>	<i>inches.</i>
January.....	4.06	5.49	1.71	1.13	1.32
February.....	3.08	5.00	1.35	0.93	0.98
March.....	3.21	4.59	0.95	1.06	1.16
April.....	1.06	1.99	0.49	0.99	0.54
May.....	1.38	1.19	0.86	0.92	0.79
June.....	0.50	0.37	0.28	0.56	0.52
July.....	0.16	0.16	0.22	0.16	0.26
August.....	0.25	0.11	0.30	0.14	0.30
September.....	0.63	0.30	0.31	0.33	0.26
October.....	1.43	1.06	0.35	0.64	0.48
November.....	2.43	2.36	0.77	0.78	0.67
December.....	3.48	4.59	1.06	1.01	1.16
Annual.....	22.50	27.12	8.65	8.65	8.44

The winter precipitation falls chiefly in the form of snow, especially on the mountains, and, aside from the relatively slight evaporation, is stored until it melts during the spring and early summer, and the greater percentage runs off to maintain the streams. As a consequence, the volume of flow of the rivers is concentrated during the spring months, as is illustrated by the following examples. As a result, the percentage of the precipitation that runs off in the streams is unusually high.

Month.	Truckee at Vista.	Carson at Empire.	Humboldt at Palisade.
	<i>acre-feet.</i>	<i>acre-feet.</i>	<i>acre-feet.</i>
January.....	40,300	15,100	6,760
February.....	52,800	20,000	12,400
March.....	85,500	28,100	37,000
April.....	116,000	40,700	66,000
May.....	149,000	79,300	67,000
June.....	98,200	74,400	79,000
July.....	42,400	32,600	32,300
August.....	23,400	6,950	4,350
September.....	23,700	2,600	2,290
October.....	34,600	8,120	4,630
November.....	40,600	9,280	5,790
December.....	37,900	11,900	5,520
Total.....	744,000	329,000	324,000
P. ct. run-off.....	55.9	58.7	11.4

¹ U. S. Weather Bureau, Summary for Nevada, 1911.

The relation of the amount of precipitation to the elevation and exposure of the instruments causes great differences in the records of stations located within a few miles of each other. For example, Reno and Verdi are located in the same valley, about 11 miles apart, Verdi being 400 feet higher and at the base of the Sierras. Reno has an average annual rainfall of 8.65 inches, while Verdi has 15.47 inches. Lewer's Ranch is about the same distance from Carson City, but is located 1,622 feet higher in the Sierras. The annual precipitation at Carson is 11.01 inches, while at the ranch the rainfall is 26.96 inches annually. Clover Valley is 18 miles south of Elko, in the East Humboldt Range and 658 feet higher. Elko has an annual rainfall of 8.44 inches, while Clover Valley has 15.00 inches. Were the Lahontan Basin a single great valley, it would be possible to form an accurate estimate of the average rainfall received at present, but as the greater number of the sparsely distributed stations of record are located in the valleys, any rainfall map of the basin as a whole drawn from the records at present available must be recognized as exaggerating the dryness of the interior of the basin and somewhat misleading. Were the records available, each of the numerous mountain ranges scattered throughout the Lahontan Basin would be surrounded by one or more closed isohyetal lines and the average annual rainfall of the basin as a whole would be rather greater than our present records lead us to believe.

Consequently, the rainfall chart (fig. 5), drawn conforming to our present data, accentuates somewhat the contrast between the heavier rainfall of the elevated rim of the basin and the interior beyond actual conditions. An earlier map, published by the Signal Service¹, based on partial records obtained during the years 1865 to 1890 and reproduced as figure 6 is probably as near correct as one drawn to-day. Nevertheless, while the maps are an expression of our present scanty knowledge, yet they show in a general way the major features of the distribution of rainfall in the Lahontan Basin.

It will be observed that the greater part of Lake Lahontan occupied the valleys which at present receive from 4 to 6 inches annual rainfall and that the amount of precipitation increases toward the borders of the drainage basin. The greatest relative amount of rainfall of the Lahontan Basin occurs along the western slope of the Sierra Mountains, reaching a maximum of 47 inches at Summit. As the slope is descended the rainfall decreases rapidly until at Reno, located near the western base of the Sierras and about 50 miles to the east of Summit, it is only 8.6 inches. This rapid decrease in rainfall prevails in the three southwestern subdivisions of the Lahontan basin along the steep eastern slope of the Sierras. In the Honey Lake Basin, however, the gradient is not so rapid and the isohyets are more widely spaced. Along the northern border of the Black Rock and Humboldt Basins the isohyetal lines trend to the east and a projecting tongue of higher precipitation follows the more elevated land forming the divide between the Great Basin and the Columbia River drainage. Similarly there is a local area of higher precipitation along the southeastern portion of the Lahontan drainage area.

RUN-OFF IN THE LAHONTAN BASIN.

Another important factor to be determined is the percentage of the rainfall that reached the ancient lake. At present each of the six major subdivisions of the Lahontan Basin supports a master stream, except the Black Rock Basin.

¹ A. W. Greely, Senate Ex. Doc. No. 287, 51st Cong., 1891.

In the Honey Lake Basin the Susan River rises along the main divide in the Sierras and, flowing through narrow mountainous valleys, enters the level valley of Honey Lake not far from Susanville. The river flows into Honey Lake, a broad, shallow body of slightly brackish water which fluctuates in area and is reported on rare occasions of drought to evaporate completely.

In the Truckee Basin the Truckee River heads in the Sierras and is the outlet of Lake Tahoe, a large body of remarkably fresh water at an elevation of 6,225 feet. From here the river flows north to Truckee and, augmented by several tributaries, flows east to Reno through a mountainous, precipitous canyon. At Reno it crosses a broad, flat intermontane valley, the Truckee Meadows, and at Vista enters another canyon which crosses the Virginia Range of mountains. At Wadsworth, after leaving the last canyon, it turns to the north and eventually enters Pyramid and Winnemucca Lakes, where the water evaporates.

The Carson River, draining the Carson Basin, is formed by two large branches heading in the Sierras. These unite near Genoa and the river flows to the northeast until it reaches Empire, just east of Carson City, where it turns to the east and crosses the Virginia Range in a precipitous canyon. Leaving the mountains near Dayton, it passes through a rather narrow valley and eventually enters the Carson Sink, a broad, flat basin approximately 50 miles in diameter. Two shallow lakes are supported by the waters

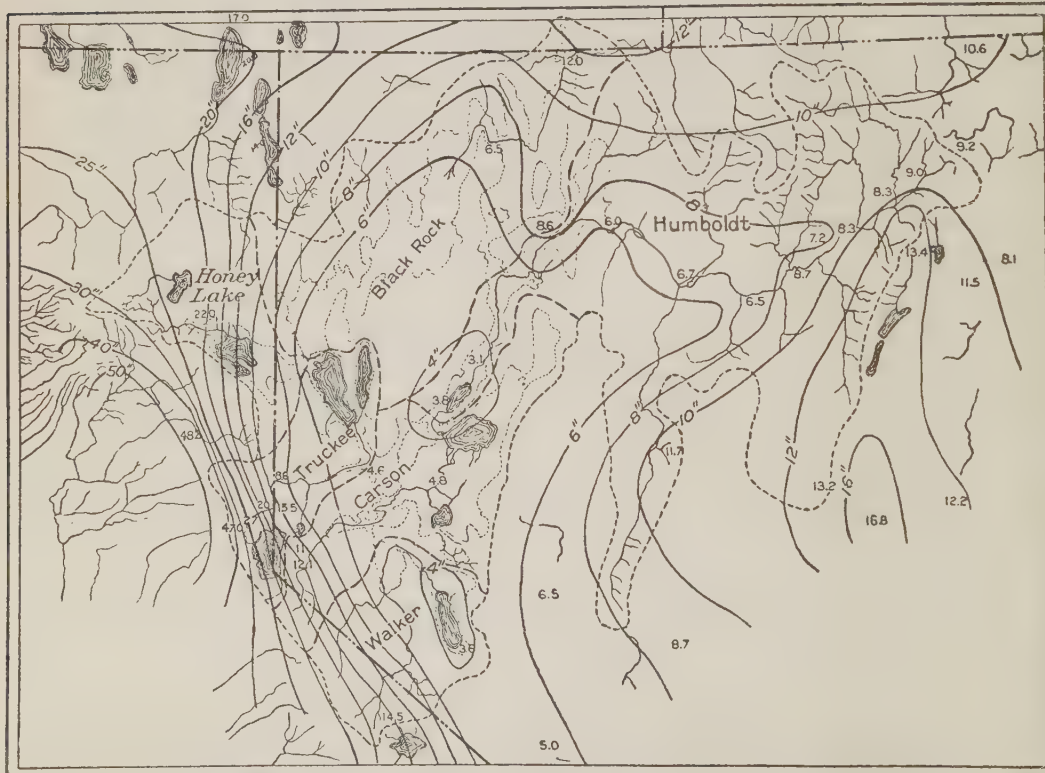


FIG. 5.—Distribution of rainfall in Lahontan Basin plotted from present-day records of U. S. Weather Bureau.

of the Carson River and in part by occasional overflow from the Humboldt River, but in times of exceptional drought both lakes are reported to go dry.

The Walker River, draining the Walker Basin, also is formed by two branches that head in the Sierras and flow northerly to their junction in Mason Valley. Here the stream continues diagonally across the valley in a rather ill-defined channel to a few miles east of Wabaska, where it turns abruptly to the southeast and follows a narrow canyon cut in the lacustrine sediments to Walker Lake.

The Black Rock Basin has several minor streams that reach the level floor and cover it with a shallow layer of water during the springtime. Usually the surface-water is evaporated by May or June, but may last until July or August in exceptionally wet years. The northern arm of the basin is drained by the Quinn River, which flows to the south and west in an ill-defined channel on the old lake bottom from near McDermitt on the Oregon line and eventually evaporates on reaching the main playa of the basin.

The Humboldt Basin is drained by the Humboldt River, which flows to the west across the several basin ranges and is formed by a number of tributaries flowing to the north and south following the intermontane valleys. It reaches the old shore-line of Lake Lahontan at Golconda and continues west in a

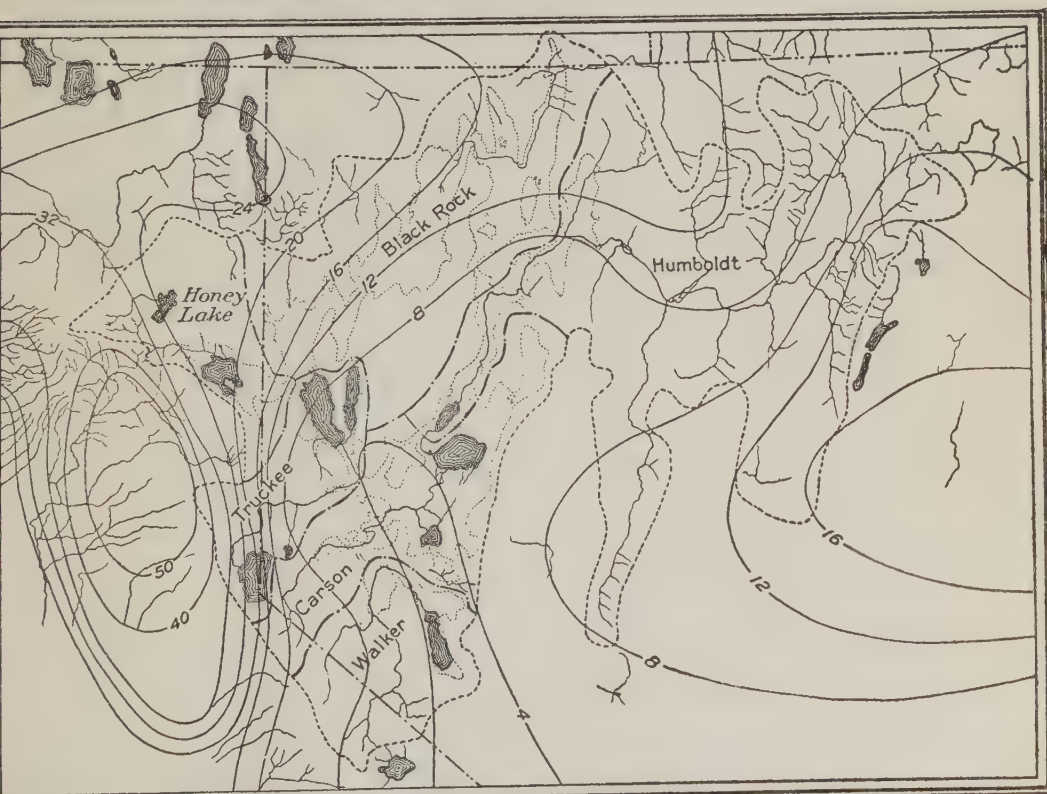


FIG. 6.—Distribution of rainfall in the Lahontan Basin 1865-1890 from records of U. S. Signal Service. Pub. 287, 51st Congress, Senate Ex. Doc.

meandering shallow channel to the northern end of the West Humboldt Mountains, where it turns to the south and follows the range. About 20 miles south, at Lovelock, it enters Humboldt Lake, another shallow, fluctuating playa lake, whose outlet is a channel cut through a lacustrine bar formed during Lahontan times. Usually the scanty overflow evaporates within a few miles of the bar, in what is known as the Humboldt Sink, but in occasional years of heavier precipitation the overflow reaches the Carson Sink.

Such data as are at present available regarding these rivers are collected in the following table:

River.	Gaging station.	Years of record.	Area basin.	Average annual flow.	
			<i>sq. mi.</i>	<i>acre-ft.</i>	<i>inches.</i>
1. Susan.....	Susanville....	1900-1, 1903-1905....	256	98,300	8.08
2. Truckee.....	Calvada.....	1899-1912.....	955	830,000	16.31
	Vista.....	1890-1892, 1897-1907..	1,750	926,720	11.79
3. Carson.....	Empire.....	1900-1908.....	988	334,400	7.54
4. Walker.....	Wabuska.....	1903-1907.....	2,420	432,800	1.721
5. Quinn River..	McDermitt....	March-May, 1911.....		59,900	.....
6. Humboldt....	Golconda.....	1901-1909.....	10,800	236,000	.2964
	Palisade.....	1903-1906.....	5,014	321,400	1.203
	Oreana.....	1901-1909.....	13,800	137,600	.184

REFERENCES.

- (1) U. S. G. S. Water Supply Paper No. 300, pp. 64, 65. (4) *Ibid.*, p. 25.
 (2) *Ibid.*, pp. 106-108. (5) Nev. Eng. Rept., 1911-12, p. 236.
 (3) *Ibid.*, No. 274, p. 127. (6) *Ibid.*, pp. 245, 201-203, 200, 204, 205.

The following table gives the average rainfall of the subsidiary basins as calculated from all stations of record available, the actual run-off, and the percentage of rainfall appearing in the streams.

River.	Years of record.	Average rainfall during period.	Average run-off during period.	Per cent of rain appearing as run-off.
		<i>inches.</i>	<i>inches.</i>	
Susan.....	3	24.68	8.08	32.7
Truckee.....	6	20.39	11.71	55.9
Carson.....	6	12.20	7.13	58.7
Walker.....	2	5.04	1.52	26.5
Quinn.....	Insufficient data.			
Humboldt.....	9	8.57	.42	4.1

The striking feature brought out in the above table is the relatively small percentage of the rainfall of the two largest subdivisions that appears as run-off in the streams.

It is for this reason that Gale¹ was led to believe that the major portion of the water of Lake Lahontan was furnished by the Truckee, Carson, and Walker Rivers. However, this is not necessarily true. While the gaging stations chosen were located at or near the former shore-lines of the ancient

¹ H. S. Gale, *Science*, n. s., vol. 41, pp. 209-211, 1915.

lake and give a fairly accurate picture of conditions at the present time, it does not follow that under the moister climate during which Lahontan existed so small a quantity of the rain that fell in the Black Rock and Humboldt Basins reached the lake.

As an extreme example the Quinn River, whose run-off at present, if measured near where it finally disappears would be but a fraction of 1 per cent, was practically obliterated by the lake during the time of high water, and whatever rain fell then would fall directly in the lake and the run-off would approximate 100 per cent. Even at present the flow of the streams draining into the Black Rock and Smoke Creek Deserts is sufficient to cover a large part of their area with a shallow sheet of water. Were this flow concentrated in a deeper and narrower valley, similar to those in which Pyramid, Winnemucca, and Walker Lakes are located, it lies entirely within the bounds of probability that a similar permanent lake would result. The evaporation from a sheet of water so thin that it may be moved bodily from one side of the flat desert floor to the other by a strong wind is certain to be greater than in a deeper permanent lake. Were the Black Rock and Smoke Creek Deserts covered by a permanent sheet of water, it is quite probable that even under present conditions the flow of the streams of the drainage basin would be approximately sufficient to maintain it.

Another factor to be considered is the actual amount of rainfall that is received by the respective subsidiary basins that form the Lahontan drainage area. Adapting the method used by White¹ in determining the relation of rainfall to run-off in American rivers, the percentage area of each subsidiary basin was obtained by planimeter measurements from the maps, the average rainfall calculated from similar measurements of the isohyetal lines on the rainfall map, and the percentage of total rainfall calculated for each subsidiary basin. The results are gathered in the following table:

Basin.	Per cent area.	Average rainfall.	Per cent total rainfall.
		<i>inches.</i>	
Honey Lake.....	7.4	17.5	14.0
Truckee.....	6.1	11.6	8.2
Carson.....	12.9	6.2	9.3
Walker.....	7.9	8.1	7.3
Black Rock.....	21.7	7.0	17.6
Humboldt.....	44.0	8.6	43.6
Lahontan....	100.0	8.9	100.0

It is to be noted that the average rainfall of the different parts of the Lahontan Basin determined by this method is not widely different, and that the bulk of the total rainfall is received by the two larger basins.

It is difficult to determine the relative distribution of the increased rainfall responsible for the existence of Lake Lahontan. An earlier map published by the U. S. Signal Service,² based on records obtained in the years 1865 to 1890 and reproduced as figure 7, is suggestive. This chart indicates the distribution of the greatest annual rainfall known at that time at the various

¹ W. F. White jr., *School of Mines Quarterly*, vol. 35, pp. 35-54, 1913.

² A. W. Greely, Senate Ex. Doc. No. 287, 51st Cong., 1891.

stations. It will be noted that the largest increase is located in the northern portion of the Lahontan Basin in Black Rock and Humboldt Basins. That the present records bear this out is indicated by the following records of the stations in operation at present:

Basin.	Station.	Years of record.	Average rain.	Maximum.	Per cent increase.
			<i>inches.</i>	<i>inches.</i>	
Honey Lake.....	Susanville.....	21	21.67	36.26	167
Truckee.....	Boca.....	40	20.34	37.58	184
	Fernley.....	40	4.62	9.08	199
	Lewers Ranch.....	32	26.96	40.95	152
	Reno.....	22	8.65	15.53	179
	Summit.....	40	47.78	76.54	160
	Truckee.....	40	26.90	43.81	163
	Verdi.....	14	15.47	23.09	149
Average.....			21.53	35.22	169
Carson.....	Carson City.....	31	11.01	18.08	164
	Fallon.....	16	4.81	5.80	120
Average.....					142
Walker.....	Hawthorn.....	26	3.56	7.36	206
	Bodie.....	12	14.49	23.62	163
Average.....					184
Black Rock.....	McDermitt.....	25	11.94	48.32	405
Humboldt.....	Austin.....	24	11.72	21.07	179
	Battle Mountain.....	40	6.71	14.03	208
	Beowawe.....	40	6.48	14.92	230
	Carlin.....	40	7.22	14.99	180
	Elko.....	40	8.44	15.58	184
	Eureka.....	13	13.77	20.64	159
	Golconda.....	32	5.96	10.02	168
	Hot Springs.....	31	3.37	10.47	310
	Lovelock.....	19	3.10	6.45	208
Average.....			7.42	14.24	203

Using the map of maximum rainfall (fig. 7), a similar calculation of the average maximum rainfall of the respective subdivisions was made with the following results:

Basin.	Per cent area.	Average maximum rainfall.	Per cent total rain.
		<i>inches.</i>	
Honey Lake.....	7.4	43.0	20.0
Truckee.....	6.1	15.6	6.0
Carson.....	12.9	7.6	6.2
Walker.....	7.9	7.3	3.6
Black Rock.....	21.7	18.8	25.6
Humboldt.....	44.0	14.0	38.6
Lahontan....	100.0	15.9	100.0

If this evidence is of any value as indicating the distribution of rainfall during the more humid period of the existence of Lake Lahontan, it would indicate that the increase occurred largely in the northern half of the drainage basin and that the Black Rock Basin actually received a greater rainfall than did the Truckee or any of the other southern basins.

From the study of the relation of rainfall to run-off in American rivers, White¹ came to the conclusion that the percentage of rainfall appearing as run-off increased with increased rainfall, although other factors made it impossible to deduce any simple law. If the data collected are of any significance, the increase in the rainfall was greatest in the northern part of the Lahontan Basin and the streams flowing into the Black Rock and Humboldt Basins would have a much greater relative increase in run-off than in the basins along the Sierras. If this be true, then it is more probable that these basins, receiving at present 60 per cent of the rain that falls annually in the Lahontan

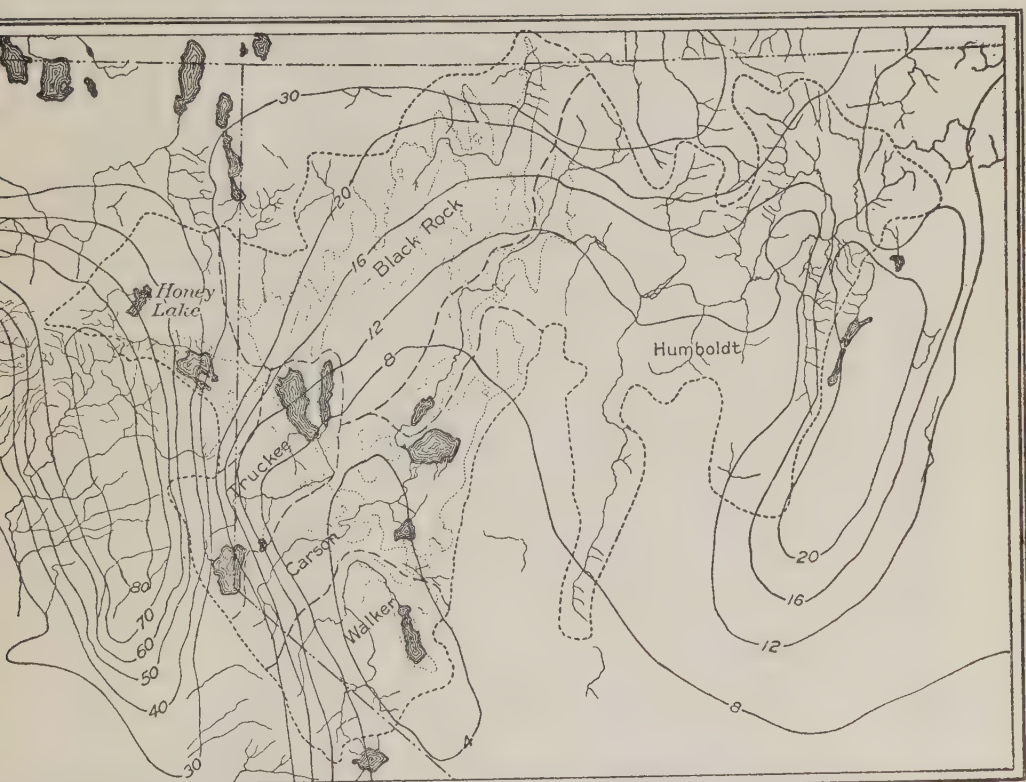


FIG. 7.—Distribution of maximum rainfall in the Lahontan Basin 1865-1890, U. S. Signal Service. Pub. 287, 51st Congress, Senate Ex. Doc.

Basin, would be able to maintain the parts of Lake Lahontan that lay within their borders without any large transfer of water from other basins. Were there such a transfer, some evidence would be left in the form of stream-channels connecting the basins.

¹ W. F. White jr., *School of Mines Quarterly*, vol. 35, pp. 35-54, 1913.

CHANNELS BETWEEN SUBSIDIARY BASINS.

The subsidiary basins of the Lahontan area are connected through narrow passes that were straits during the higher stages of the lake. As the level of the lake fell toward the elevation of the divides, large bars were frequently developed across the channels. Almost invariably these bars grew at right angles to the walls of the passes and nearly or completely closed the channels. As the lake fell these bars should have been easily truncated or channeled if there had been any considerable flow between the basins. In the entire Lahontan area there are but two instances where this has happened—the outlet of Humboldt Lake through the bar closing the southern end,¹ and the truncation of the bar at the head of Winnemucca Lake by the Truckee River.² Elsewhere the bars are intact and unchanged since the lake abandoned them.

The Truckee Basin is connected with the Black Rock Basin at the northern end of Pyramid Lake through Emerson Pass, with the Honey Lake Basin through Astor Pass, and with the Carson Sink across an ill-defined divide near Fernley. The latter divide is about 300 feet above Pyramid Lake, and there is no evidence apparent at present that would suggest a flow between the two basins during the existence of Lake Lahontan.

The divide in Astor Pass is 150 feet above Pyramid Lake and has several transverse bars extending nearly across it. The largest and best developed is located at the western end of the pass and extends from the south wall about 2,500 feet north concentric with the arm of the Honey Lake Basin into which the pass leads. Behind the bars are several undrained mud flats, demonstrating the lack of any overflow through the pass in either direction.

Emerson Pass is, however, less than 75 feet above Pyramid Lake, and had there been any considerable outflow from Pyramid and Winnemucca Lake Basins it would have passed here into the Smoke Creek and Black Rock Basins. As the evidence here is crucial the pass will be described in detail.

The eastern wall of Emerson Pass is the steep, rugged Lake Range which forms the dividing mountains between Pyramid and Winnemucca Lakes to the south. Low, gently sloping hills form the western boundary of the pass. When Lake Lahontan was at its height the strait through the pass was about 2 miles wide, but as the waters fell the strait was constricted until at the last it had a minimum width of 400 feet. This was largely due to the gentler slopes of the western hills, but was accentuated at either end of the pass by large alluvial fans developed by large streams descending the precipitous slopes of the Lake Range.

The southern end of the pass adjacent to Pyramid Lake is closed by two barrier beaches concentric with the head of the lake, the highest being 38 feet above the water-level in 1914. About 2 miles from the lake the pass is greatly constricted between a hill to the west and a broad fan extending a mile out from the Lake Range. The pass here reaches its first summit, a mud-flat about a mile long and 71 feet above the lake. In the next 2 miles the pass descends 20 feet and broadens as a flat-floored valley until it reaches a bar extending from the western hills and nearly closing the pass. Around the bar the pass turns abruptly to the west and follows the foot of the large alluvial fan that sweeps out 1.5 miles from the Lake Range. Another long

¹ I. C. Russell, Mono. 11, U. S. Geol. Surv., p. 106, plate 18.

² *Ibid.*, p. 120, fig. 19.

mud-flat or playa marks the low point, 24 feet above the lake, between the summits of the pass as it turns to the north again around the fan.

From the end of the mud-flat and about a mile from Sano, a section-house on the Western Pacific Railroad located at the junction of the pass and the Smoke Creek Desert, the pass rises again and reaches an elevation of 78 feet above the lake at the junction of a short bar from the west and the alluvial fan from the east. Beyond the pass opens out into the Smoke Creek Desert as a broad, flat valley covered with a thin veneer of sand dunes which soon give way to the typical playa muds. The lowest point of the Smoke Creek Basin is located some 20 miles to the north and is 20 feet below the 1914 surface of Pyramid Lake.

The bars mentioned were built by Lake Lahontan when it stood near the level of the thinolite terrace. The other terraces of the old lake are clearly marked on the walls of the pass and on the surfaces of the large fans extending from the Lake Range. The tufa deposits are largely limited to the upper faces of the bars and the terrace 140 feet above the thinolite terrace. The tufa accentuates the steepness of the bars and the alluvial fans below the thinolite terrace and is largely responsible for the channel-like appearance of the pass.

There is no doubt but that the pass is pre-lacustrine in origin, as is shown by the terraces cut by the lake in the slopes of the hills and the alluvial fans. The modification of the pass by the lake is slight and consists chiefly in the formation of the bars and reworking of the surface gravels of the fans to some extent. The terraces continue through the pass at the same elevations at which they are found in the Pyramid and Smoke Creek Basins, and the thinolite terrace is the best developed as in the other basins.

The post-lacustrine changes have been exceedingly slight, and consist of a shallow trenching of the old beach-lines and the deposition of small fans at the foot of the slopes. One of these buries the nose of the bar near Sano to a depth of 5 to 10 feet, accentuating the elevation of the summit of the pass, but is not of sufficient area to conceal any stream-channel that might have existed.

The interpretation of the evidence leads to but one conclusion, that as the pass was uncovered by the receding lake there was no overflow into the Smoke Creek Basin. Had there been any overflow, the outlet of the lake would have easily eroded the fine clays and silts now forming the summits of the pass. Any channel produced would still be evident in the fine clays and sands covering the slope of the Smoke Creek Basin near Sano.

Further evidence may be had from the tufas. As has been shown, the *Chara* marl and the upper limit of the thinolite seem to indicate a rather definite concentration of the calcium carbonate in solution in the lake waters. The elevation at which they appear should give a clew to the composition of the respective bodies of water from which they were deposited. Careful determination of these elevations by means of an alidade in the Black Rock, Smoke Creek, and Pyramid Basins indicated that they corresponded to a foot at all points measured. This would lead to the conclusion that as far as the content of calcium carbonate was concerned the waters of the three basins were essentially the same.

The fact that the amount of tufa deposited in the Pyramid and Winnemucca Lake Basins corresponded closely with that which should have been deposited to furnish the present amount of sodium and potassium in these two lakes further suggests that there has been but little if any salt washed out of their basins through overflow into the Black Rock Basin.

Although it must be admitted that some of the foregoing evidence is based on conjecture, but as accurate as our present data admit, yet it has a cumulative value that leads to the belief that the determination of the age of Lake Lahontan based upon the present rate of accumulation of salt in Pyramid and Winnemucca Lakes is not far from the truth. The evidence so far advanced is summed up in the following table:

Method of calculation.	Age of Lahontan.
	<i>years.</i>
Rate of accumulation of chlorine from Truckee River.....	3,880
Rate of accumulation of sodium from Truckee River.....	2,450
Accumulation of chlorine in last 31 years.....	1,956
Rate of concentration of chlorine by evaporation.....	2,400

In a discussion of preliminary results Huntington¹ believes that the time necessary for the accumulation of the salts at present in Pyramid Lake is 2,000 years, as the additional salts carried in by the minor streams should be added to the burden of the Truckee River in the first two calculations, thus shortening the length of time necessary. We may note that the last two determinations which are free from this criticism are approximately 2,000 years.

Two independent determinations of the geologic age of inland lakes in the vicinity of the Lahontan Basin are of importance. Gale² found that it would take the Owens River 4,200 years to supply the chlorine and 3,500 years to supply the sodium in Owens Lake at the present rate of accumulation. Owens Lake, however, previously overflowed, so that these figures represent only the saline residue and accumulation since the lake fell below its outlet.

Albert and Summer Lakes, located a short distance northwest of the Lahontan Basin, are the remnants of a larger lake contemporaneous with Lake Lahontan. The basin in which they are found is similarly without an outlet. Van Winkle³ determined the geologic age of the ancient lake, based upon the present rate of accumulation of salt, as 4,000 years.

Huntington's⁴ work on the climatic changes of recent time in the western part of North America probably gives the most accurate methods of dating the periods of heavy rainfall available at present. In a study of the sequoias of California he was able to determine a relation between the annual growth of the trees and the amount of rainfall. Further study of the historical records and ruins of the southwestern part of the continent gave him much corroborative evidence, and he was able to construct a rainfall curve giving a detailed history of the wet and dry periods for the past 2,500 years. These show a period of heavy rainfall immediately preceding the Christian era, and it is probable that the history of Lahontan began at this time.

¹ Ellsworth Huntington, *Civilization and climate*, p. 234.

² H. S. Gale, U. S. Geol. Surv. Bull. 580, p. 264, 1914.

³ Walton Van Winkle, U. S. Geol. Surv., Water Supply Paper 363, p. 123, 1914.

⁴ Ellsworth Huntington, Carnegie Inst. Wash. Pub. No. 192, 1914.

HISTORY OF LAKE LAHONTAN.

Thus far we have only determined that the history of Lake Lahontan began about the time of Christ. There remains the task of working out the details of its story as far as possible. The more significant records are found in its former beach-lines and the sediments deposited in the ancient lake.

TERRACES.

Russell¹ made a very careful study of the shore phenomena, and gives a very accurate and detailed account of the beach-lines, bars, and deltas found in the Lahontan basin, which renders a repetition unnecessary in the present paper. He was unable, however, to correlate the beach-lines between the different basins. During the present study several sections, distributed in the major basins and showing well-developed series of terraces, were measured with an alidade and plane table and accurate profiles obtained. A typical profile is shown plotted to true scale as figure 8. There are seven rather well

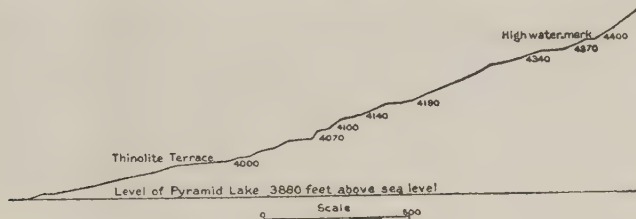


FIG. 8.—Profile of Terraces shown in Fig. 22.

marked beach-lines that are usually represented in the different basins. The lowest of these, the thinolute terrace, occurs at an elevation of 4,000 feet above sea-level or 120 feet above the present level of Pyramid Lake. In most instances it is a double terrace, the two levels differing about 10 feet in elevation. It is the only terrace that is cut in rock as at Anaho Island. It apparently marks a level at which the Lake was fairly stable for a long period of time. As tufa deposits of the dendritic type are found on its sea face, it was probably formed during the earlier history of the lake, before it finally rose to its maximum height.

The remaining well-developed terraces fall into two groups of four and two respectively. The first group lie at elevations of 4,070, 4,100, 4,140, and 4,190 feet above sea-level; the second at 4,340 and 4,370 feet. These terraces can be recognized in favorable localities in all of the basins. It must be remembered, however, that with the exception of the thinolute terrace, the beach-lines are formed only in unconsolidated sediments, and then only where the loose and easily worked materials are abundant. In all of the sections measured, other slightly developed beach-lines are recognizable that do not correlate well between the different sections, but the ones mentioned are the most constant and best developed.

The unconsolidated material in which the beach-lines are cut necessarily shows only the latest stage of wave-action. Any previous water-line would be

¹ I. C. Russell, U. S. Geol. Surv. Monograph 11, pp. 99-123.

obscured and even obliterated by the waves as the water again rose above the older beaches. This is well shown by Russell's careful though unsuccessful search for evidence showing successive periods of high water. Consequently, the present beach-lines represent only the high-water marks of stages subsequent to the period of greatest depth of the lake or recessional beaches formed by the falling waters as they shrank to the present-day residual lakes.

SEDIMENTS.

The lake sediments are exposed in sections only in the canyons of the Truckee, Humboldt, and Walker Rivers. Russell¹ believed he recognized a bed of intermediary gravels separating the lacustrine clays. If his interpretation is correct, there were two stages of high water separated by a period of desiccation. His general section follows:

Generalized Section of Lahontan Sediments (according to Russell).

	Average thickness in feet.
Upper lacustral clays:	
Evenly laminated marly clays, fine and homogeneous, usually saline; with interstratified bands of dendritic tufa near the top; in places containing intercalated layers of volcanic dust. In some places this member is divisible into three parts, the upper and lower being normal clays, while the intermediate member is more sandy, and usually contains iron-stained layers, that are frequently contorted.	50 to 75
Fossils: <i>Cypris</i> , <i>Anodonta</i> , <i>Margaritana</i> , <i>Sphærium</i> , <i>Pisidium</i> , <i>Helisoma</i> , <i>Gyraulus</i> , etc., together with mastodon or elephant, horse, and camel.	
Contact unconformable.	
Medial gravels:	
Cross-stratified sand, gravel, and loam, in beds that are irregular both in thickness and inclination, frequently forming arches of deposition; at times exhibiting two plainly marked divisions, the upper being a compact, earthy, homogeneous flood-plain deposit, the lower clean, well-rounded sand and gravel, at times strongly cross-bedded.	50 to 200
Fossils: <i>Anodonta</i> , <i>Cyraulus</i> , <i>Lymnophysa</i> , <i>Pompholyx</i> .	
Contact unconformable.	
Lower lacustral clays:	
Laminated marly clays, very similar to the clays at the summit of the section. The clays throughout the section frequently exhibit two systems of joints at nearly right angles to each other (full thickness not exposed) . .	100
Fossils: <i>Pompholyx</i> .	

In the restudy of the sections exposed in the canyons mentioned, the conclusion was reached that only in the Truckee Canyon were all three members lacustrine sediments. In the Humboldt and Walker River Canyons the gravels and lower clays are typical alluvial-fan and playa deposits, while only the upper clays were laid down by the ancient lake.

MEDIAL GRAVELS.

In the Truckee Canyon the general relations of the sediments are well shown in McGee's sections² and in detail as he described them. The medial gravels are cross-bedded and have a typical bar structure clearly

¹ I. C. Russell, U. S. Geol. Surv. Monograph 11, pp. 126-146.

² I. C. Russell, U. S. Geol. Surv. Monograph 11, pp. 131-136.

showing, as Russell states, that they were deposited during a stage of low water. As the canyon is ascended from the Agency bridge, the gravels become coarser until the Narrows are reached, when they pinch out and disappear. Here the tripartite division of the lacustrine sediments is obscure and there are several alternations of lake silts and gravels. If the assumption that the gravels represent stages of low water and that their thickness is proportional to the time interval that elapsed during their deposition, there are at least two and possibly three stages of low water, the first being the shorter.

In the Humboldt valley the gravels are reddish gravelly sands and loams typical of alluvial-fan deposits. The lake clays rest unconformably upon them, as is shown in the general section drawn by McGee.¹ The section, however, does not express the wide variation in the sections at different locations along the river in the sediments below the lake clays. This can be glimpsed to some extent from the variation from marls to gravels that Russell correlated as the "lower lacustral clays."

There is no well-marked dividing-line between the "gravels" and "lower clays" and they apparently belong to the same series. Rapidly alternating beds of highly oxidized gravels, sands, silts, and loams are characteristic of alluvial aprons and those here seen are believed to be the valley-fill over which Lake Lahontan spread and deposited its sediments.

About 3 miles north of Oreana, as shown by Russell,² in section C, the lake-beds include a small bed of loam or alluvium that tapers to the north, where it can be followed for several miles as a white line. This evidently represents a low-water stage in the lake.

In the Walker Canyon the sediments of Lake Lahontan are the "upper lacustral clays" of Russell.³ The section given is a true representation of the relations of the sediments. The gravels again are a rapidly alternating series of cross-bedded, lenticular, and highly oxidized pebbly clays, silts, and sands entirely similar to alluvial fans and aprons. The lower beds are somewhat more argillaceous, with rounded concretions up to 6 inches in diameter, but no true tufa.

The "dam" is a typical alluvial fan which, extending from the mountains on the west and meeting a similar fan from the hills to the east, formed a divide between Mason Valley and the valley of Walker Lake. The low point in the divide was within 10 feet of the high-water mark of Lake Lahontan. This explains the apparent elevation of the "medial gravels" on the eastern side of the valley which puzzled Russell,⁴ and led him to assume that the Lahontan sediments had been displaced 150 feet by a fault.

It will be noted in Russell's section that the fossils found in the lacustrine sediments were confined to the "upper lacustral clays." If the present view that the "medial gravels" and "lower lacustral clays" are alluvial deposits which the lake overflowed during its rise and expansion, the explanation is obvious. The animals, especially the snails and fishes, could not live in the basin until the lake and the attendant moister climate had made the environment suitable to their existence.

¹ Russell, U. S. Geol. Surv. Monograph 11, plate xxiii.

² U. S. Geol. Surv. Monograph 11, p. 130.

³ I. C. Russell, U. S. Geol. Surv. Monograph 11, section C., plate xxviii.

⁴ U. S. Geol. Surv. Monograph 11, p. 142.

HISTORY OF WALKER RIVER.

One of the most significant features connected with the history of Lake Lahontan is the course of the Walker River. At present the river, a sluggish, meandering stream, flows in a shallow channel northward through Mason Valley. As it reaches the northeastern boundary of the valley, about 6 miles east of Wabuska, the river turns abruptly to the southeast, its grade steepens, and it enters the canyon cut through the old alluvial dam that formerly marked the divide between Mason Valley and the valley of Walker Lake.

Leading from the northwestern corner of Mason Valley is a well-developed channel, with steep walls from 500 to 800 feet high, known as Churchill Canyon. This leads to the Carson River and is followed by the Southern Pacific Railroad. The canyon is about 300 feet wide at its narrowest point, is flat-bottomed, and bears evidence of having been occupied by a stream of considerable size. At present only a small amount of water supplied by the snows melting in the springtime flows through the canyon, and during the greater part of the year it is dry.

At the northern end of Mason Valley an old stream-channel, similar in all respects to the present channel of the Walker River, can be traced from the head of Churchill Canyon to the river opposite Mason Butte. A difference of 10 feet in the elevation of the river would turn it down the old channel through Churchill Canyon into the Carson River.

The evident conclusion is that previous to the existence of Lake Lahontan the Walker River was a tributary of the Carson. As the lake rose it gradually drowned the river through Churchill Canyon and, spreading in Mason Valley, eventually overflowed the "dam" into the valley of Walker Lake. The overflow easily cut a channel through the unconsolidated alluvium forming the dam, and as the lake receded the channel was deepened below the older prelacustrine channel and the Walker River has followed it ever since. As the top of the dam is within 10 feet of the maximum high-water mark of Lake Lahontan, Walker Lake did not come into existence as a part of the greater lake until the latter had reached its greatest extent.

A determination of the age of Walker Lake should give a clue to the date of the highest stage of Lake Lahontan. Walker Lake at present contains 2.59 cubic miles of water. The average inflow of the Walker River is 0.0985 cubic mile annually. It would take the river 26.1 years to fill the lake to its present level. As the lake-water contains 44.56 times as much chlorine as the river, it would take the river 1.163 years to supply the chlorine in Walker Lake.

The uncertainties as to the relation of the present annual contribution of chlorine of the river to the lake and amounts in the past have already been covered. A further uncertainty is the amount of salts in the Walker Lake basin previous to its connection with Lake Lahontan; for with the moister climate a small lake may have been present at the time Lahontan overflowed the "dam." The present drainage of the Walker Lake Valley contributes very little flow to the lake and it is probable, even with the moister climate of Lahontan times, that the independent lake was small and with little salt.

Using the annual evaporation from the lake as an alternate method, it would take 1,300 years to concentrate the chlorine present if the lake remained at its present size. At the time of high water, however, it was twice its present size and the corrective factor to be applied is difficult to estimate. From the

fact that the abandoned strand-lines are feebly developed it is assumed that the lake fluctuated rather rapidly and probably fell at a gradually decreasing rate, due to the shrinking area of water-surface tending to diminish the total annual evaporation. Probably 30 to 40 per cent correction will bring the results somewhere near the truth, and the time of overflow from the main body of Lahontan was between 800 and 900 years ago.

OUTLINE OF THE HISTORY OF LAKE LAHONTAN.

With the available data, the outline of the story of Lake Lahontan can be sketched. The lake had its beginning between 2,000 and 4,000 years ago, and reached its maximum depth and extent about 1,000 years ago. For a closer approximation it is necessary to appeal to the work of Huntington¹ on the sequoias.

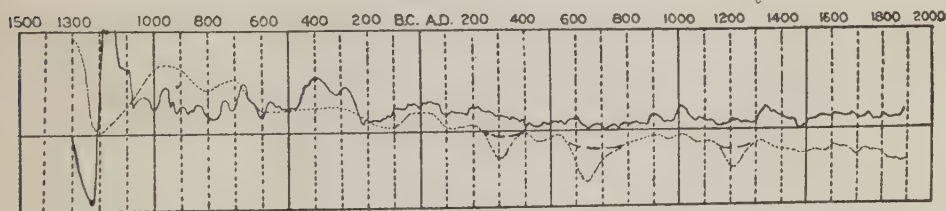


FIG. 9.—Climatic curve determined by measurement of the annual growth of sequoias. *The Climatic Factor*, Ellsworth Huntington, Pub. No. 192, Carnegie Inst. Wash., p. 172.

His rainfall curve, reproduced as figure 9, shows wet periods about the time of Christ, 1000 A. D. and 1350 A. D. Lake Lahontan had its beginning during the first period about 2,000 years ago, and reached its maximum depth during the second about 1000 A. D. The thinolite terrace probably was cut during the early history of the lake within the first wet period, when the level of the Lake was fairly stationary. It is possible that the medial gravels in the Truckee Canyon were deposited at this time, as the rock at the Narrows which furnished the material for the gravels, is mainly exposed at the level of the thinolite terrace.

The dating of the other terraces is more difficult. The uppermost terrace, within 30 feet of the high-water mark, probably corresponds to the time the overflow into the Walker Lake Basin was cutting its channel. None of the others can be correlated, although they were probably formed by the third rise of the lake.

The bulk of the tufa deposits probably was formed during the closing periods of the lake history, for there is scanty evidence of any pause during its deposition.

CONDITIONS NECESSARY FOR EXISTENCE OF LAKE LAHONTAN.

It is of interest to approximate as closely as may be the conditions necessary for the existence of Lake Lahontan in order that some picture of the actual conditions may be formed. When Lake Lahontan was at the high-water mark it had a surface area of 8,450 square miles. The area draining into the

¹ Ellsworth Huntington, Carnegie Inst. Wash. Pub. No. 192.

lake was 45,730 square miles. On the various assumptions as to evaporation and percentage of rain that fell on the drainage area reaching the lake, the following average rainfall in inches would be necessary to support the lake at a constant level.

Evaporation.	Percentage run-off.				
	20 p. ct.	25 p. ct.	30 p. ct.	35 p. ct.	40 p. ct.
<i>inches.</i>	<i>inches.</i>	<i>inches.</i>	<i>inches.</i>	<i>inches.</i>	<i>inches.</i>
50	46.2	36.9	30.7	26.9	23.1
45	41.9	28.1	27.6	24.2	20.8
40	37.6	24.9	24.6	21.5	18.5
35	32.6	21.7	21.0	18.8	16.2
30	27.6	18.4	18.5	16.1	13.9

A similar calculation for the old lake when it stood at the level of the thinolite terrace is as follows:

Evaporation.	Percentage run-off.				
	20 p. ct.	25 p. ct.	30 p. ct.	35 p. ct.	40 p. ct.
<i>inches.</i>	<i>inches.</i>	<i>inches.</i>	<i>inches.</i>	<i>inches.</i>	<i>inches.</i>
50	20.2	18.9	13.5	12.0	10.1
45	18.2	16.9	12.1	10.8	9.1
40	16.2	14.9	10.7	9.6	8.1
35	14.1	12.9	9.3	8.4	7.1
30	12.1	10.9	8.0	7.2	6.1

At present the average rainfall of the Lahontan Basin is approximately 10 inches, the evaporation 50 inches, and the run-off 22 per cent. Under these conditions it would take about four times the present rainfall to support the lake at its former high-water mark or about twice the present rainfall to

	Wet years.		Dry years.	
	Rainfall at Truckee.	Evaporation at Lake Truckee.	Rainfall at Truckee.	Evaporation at Lake Truckee.
	<i>inches.</i>	<i>inches.</i>	<i>inches.</i>	<i>inches.</i>
January.....	8.37	0.89	1.60	1.33
February.....	12.19	.58	2.62	1.00
March.....	8.68	.90	3.55	1.41
April.....	2.60	2.00	1.27	1.78
May.....	3.70	2.26	0.67	2.48
June.....	0.64	3.14	0.00	4.24
July.....	0.45	3.40	0.00	4.70
August.....	0.78	4.00	0.00	5.29
September.....	1.32	3.69	0.15	4.09
October.....	3.21	2.75	0.44	3.48
November.....	5.08	2.47	1.06	2.09
December.....	4.16	1.02	1.62	1.58
Total.....	51.18	27.10	13.98	33.47

support it at the level of the thinolite terrace. But with increased rainfall the evaporation would decrease. This is illustrated by the evaporation determination made for six years at Lake Tahoe by Duryea.¹ The mean evaporation of the three wet years was compared with the mean evaporation of the three dry years, as indicated by the rainfall at Truckee.

In this particular instance the evaporation decreased to about 80 per cent when the rainfall was $3\frac{2}{3}$ times as great.

The percentage of run-off increases when the rainfall increases, as is indicated by the following records of the Truckee River at Vista:

Year.	Rainfall of basin.	P. ct. of mean rainfall.	Run-off.	P. ct. of rain appearing as run-off.
	<i>inches.</i>		<i>inches.</i>	
1903	15.28	82.2	7.04	46.0
1904	26.19	140.9	17.52	66.8
1905	12.31	66.2	6.21	50.4
1906	21.79	117.2	14.39	66.0
1907	26.08	140.3	17.58	67.4

Similarly, White² found there was a definite increase in the percentage of run-off with an increased precipitation, but not in direct proportion. While no definite relation is known, yet if the percentage of run-off increased to 30 per cent and the evaporation decreased to 45 inches, only $2\frac{1}{2}$ times as much rainfall would be needed to support Lake Lahontan at the high-water mark; and it is believed that this is approximately the condition that caused the expansion of the ancient water-body.

LAHONTAN FAUNA.

The most startling result of the limitation of Lahontan history to recent years is found in connection with the fact that many of the animals found in its sediments are extinct or no longer exist in the region, and it will be necessary to change present conceptions of the length of time necessary to radically alter a mammalian fauna. Russell³ mentions the presence of the remains of horses, elephants, and camels, and in the upper beds of the Lahontan sediments in the canyon of the Walker River found a spear-point of human manufacture buried 25 feet below the surface in the lacustrine clays.

During the construction of the branch of the Southern Pacific Railroad through Astor Pass, a large gravel-pit was opened in a bar of Lahontan age. Numerous teeth and bones were found in the upper layers of the gravel which were submitted to Dr. J. C. Merriam⁴ for determination. The animals represented were *Felis atrox*, a species of lion also found at the Rancho La Brea; a species of horse related to either *Equus pacificus* or *Equus occidentalis* but possibly different from both; and a camel near *Camelops*, a form also found in the Rancho La Brea. All of these forms are now extinct and neither

¹ Edwin J. Duryea, Eng. News., Feb. 29, 1912.

² W. F. White jr., School of Mines Quarterly, vol. 35, pp. 35-54, 1913.

³ U. S. Geol. Surv. Monograph 11, p. 143.

⁴ J. C. Merriam, Cal. Univ. Bull., Dept. Geol., vol. 8, pp. 377-384, 1915.

camels nor lions are found on this continent as a part of the present native fauna. Nevertheless, other animals have been known to become extinct within historic times, as, for example, the aurochs of Europe, and there is no reason to conclude that Lahontan must have existed at some long period in the past simply because some of the animals that lived during its existence have now completely disappeared from the region.

All of the physical evidence points to the recent existence of the old lake. The terraces, bars, and other lacustrine features are to-day practically as fresh and unchanged as when they were first formed by the lake waters. Instrumental determination of the elevation of the high-water level over the entire basin, with the exception of Walker Lake, showed that the shore-lines had not suffered any deformation whatever. As the mountain ranges of Nevada are bounded by faults on one or both sides and movement is still in progress¹ along certain of them, it is surprising that there has not been some change in the elevation of the lacustrine beaches.

With the exception of an occasional scarring of the terraces by cloud bursts, there has been practically no erosion of the beach-lines. In only a few localities have the lake sediments been covered by wash from the surrounding hills, and then only to a depth of 1 or more feet. In brief, all of the evidence bearing on the age of the former lake seems to clearly indicate that the history of Lake Lahontan has all taken place within the past few thousand years.

¹ J C. Jones, Bull. Seism. Soc. Am., vol. 5, pp. 190-205, 1915.

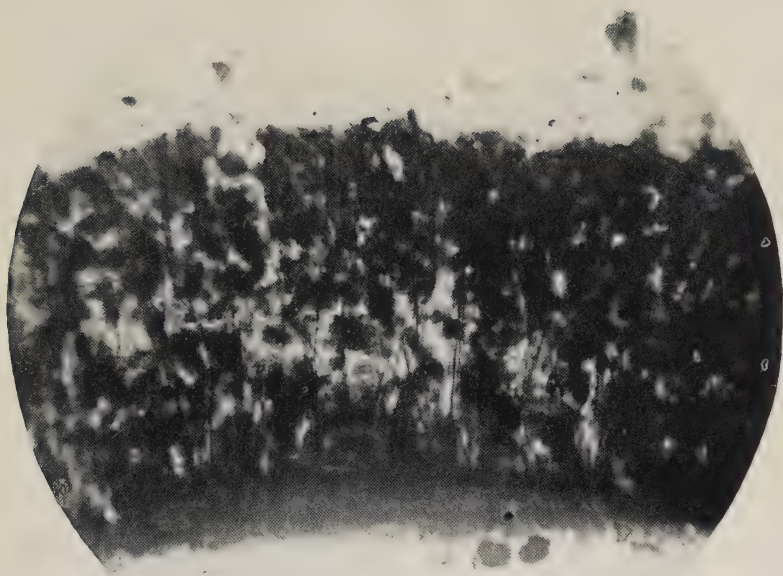


FIG. 10.—Microphotograph of recent tufa forming in the Salton Sea. $\times 100$.

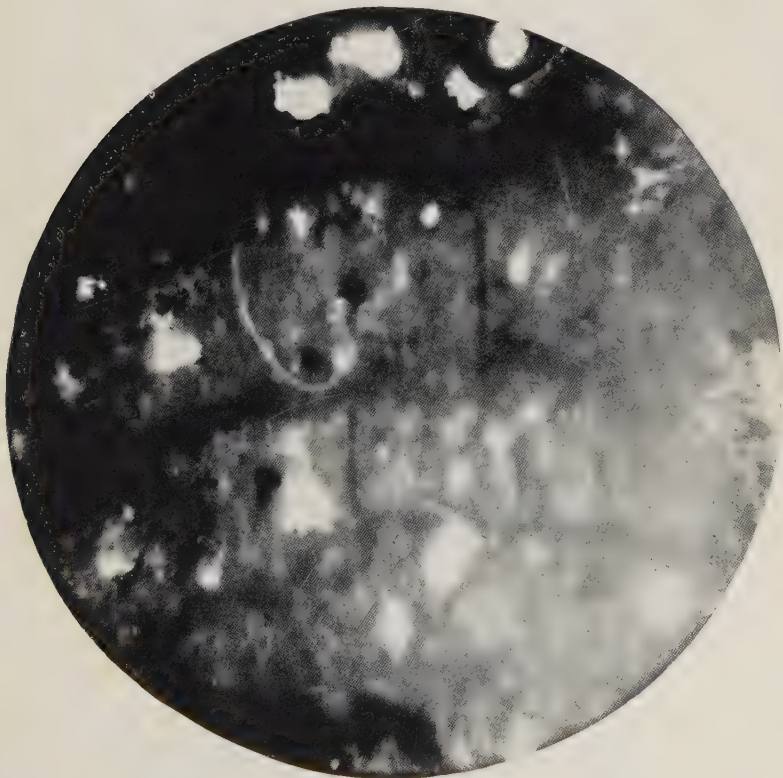


FIG. 11.—Microphotograph of Blake Sea tufa at Travertine Point, Salton Basin. $\times 100$.





FIG. 12.—Tufa at Travertine Point, Salton Basin. Note tendency of tufa to grow outward and upward toward the source of light. Photographed by D. T. MacDougal.



FIG. 13.—Lahontan tufa 135 feet above Pyramid Lake, Anaho Is.



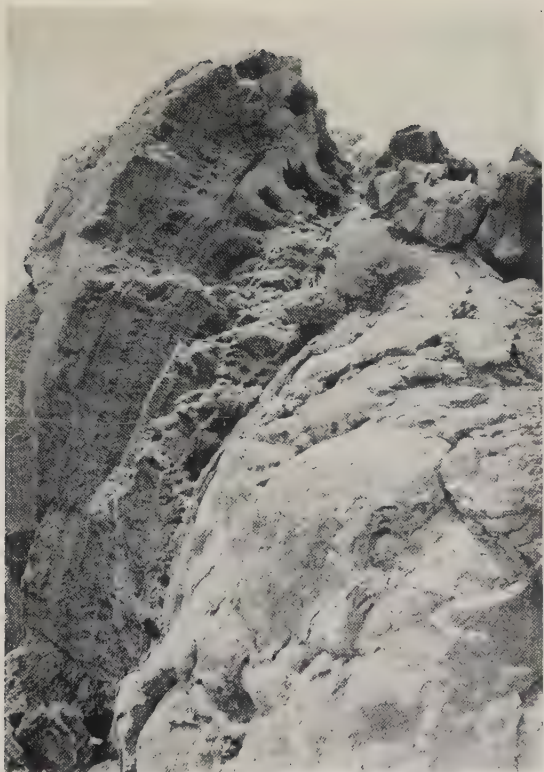


FIG. 14.—Lahontan tufa at edge of Thinolite Terrace, southwest corner of Anaho Island, Pyramid Lake.



FIG. 15.—Detail of Fig. 14, showing layers of thinolite tufa.





FIG. 16. Lahontan tufa at an elevation 400 feet above Pyramid Lake, north of Anaho Island.

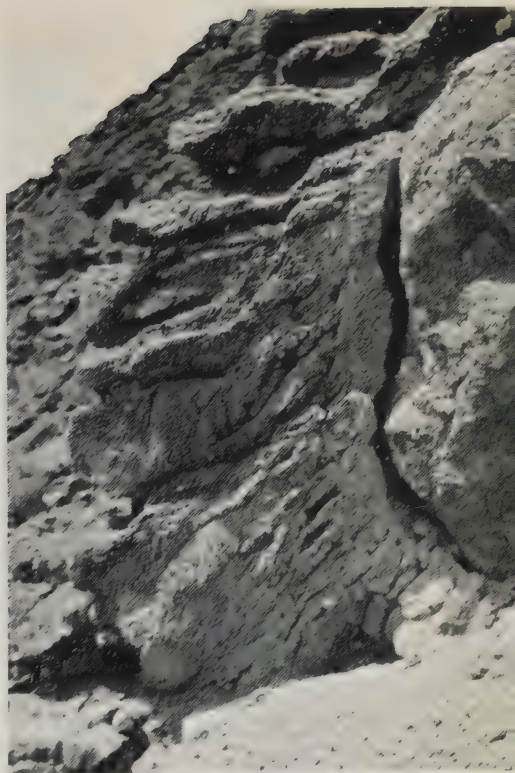


FIG. 17. Lahontan tufa 200 feet above Pyramid Lake, south slope of Anaho Island.

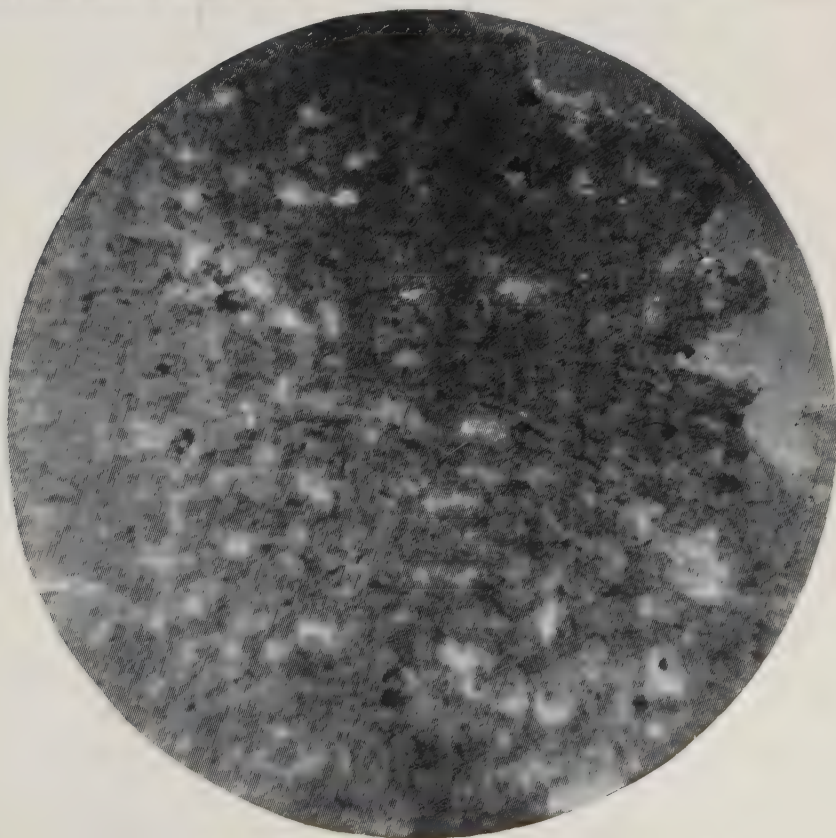






FIG. 19.—Lahontan tufa 150 feet above Pyramid Lake, west slope of Anaho Island.



FIG. 20.—Tufa composed largely of casts of chara 150 feet above Pyramid Lake, Anaho Island. Natural size.





FIG. 21.—Fallen tufa tower showing concentric growth of tufa. Note absence of conduit in center.



FIG. 22.—Terraces of Lake Lahontan. Terrace Point, north end of Pyramid Lake.



ON THE PLEISTOCENE HISTORY OF THE
GREAT BASIN.

BY ERNST ANTEVS,
University of Stockholm.

Three Plates and Nineteen Text-figures.

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ON THE PLEISTOCENE HISTORY OF THE GREAT BASIN.

INTRODUCTION.

The researches of G. K. Gilbert and I. C. Russell on the Pleistocene Lakes, Bonneville in Utah, Lahontan in Nevada, and Mono in California, have made the Great Basin the classical field for studies of many geographical and geological features, not only because of the marvelous distinctness and development of the phenomena but because of the masterly way in which they were described and interpreted.

The president of the Carnegie Institution of Washington, Dr. John C. Merriam, in 1922 requested the writer to study the deposits in the ancient Bonneville, Lahontan, and Mono Lakes in order to increase our knowledge of their Pleistocene history and more accurately to connect this with the history of the northern part of the continent. The months of July and August were devoted to this work.

It was hoped that the clays deposited in the lakes would show annual lamination, eventually enabling direct correlation between the high-water stages in the Great Basin and the disappearances of the ice-sheets in the north, but the sediments were found on the whole to lack seasonal banding. The times of the lakes, therefore, are discussed from a broad climatologic basis. An analysis and review of the climatic conditions during glaciations and during the post-glacial epoch are given. The chief events in the Great Basin are found to have run parallel with the main events in the north. The expansions of the waters are ascribed to the combined effect of little evaporation, due to low temperature, and of greater precipitation, caused by the climatic change which checked the expansion of the ice-sheets and caused their disappearance. The highest stands of the lakes coincided with the glaciations in the adjacent mountains and with the maximum extension of the land ice and the beginning of its shrinking. In all probability there were as many high-water stages as there were glacial epochs, though traces of all are not found, on account of the scarcity of exposures. In the Lahontan Basin records of three and perhaps four distinct lake-stages are described. During the intervening periods, corresponding to the interglacial epochs, the basins were deserts as to-day.

The working up of this report was done primarily at the American Geographical Society of New York and very much facilitated through Dr. Isaiah Bowman's courtesy and unrestricted admission to the excellent library of the society. The work was also aided by the kind interest of the American Scandinavian Foundation and the Scandinavians in New York, and by valuable information of Professor J. Claude Jones, of the University of Nevada, and of Professor Frederick J. Pack, of the University of Utah.

I. FACTORS AND CONDITIONS OF GLACIATION AND DEGLACIATION.

CONTEMPORANEITY OF PLEISTOCENE GLACIATIONS.

The retirement of the last ice-sheet from central Scania, the southernmost province of Sweden, as determined by Gerard De Geer's and Ragnar Lidén's geochronological studies of seasonally banded or varved clays, began about 14,000 years ago. Of this time, 5,000 years were occupied by shrinking of the ice to small remnants, and 8,500 to 9,000 years constitute the post-glacial epoch (De Geer, 1914; Lidén, 1911; Sandegren, 1924, p. 43; see Antevis, 1922, 1922a).

The length of time occupied in the uncovering of southwestern Scania and the Danish Islands is not known. Coordination of Milthers's (1918; 1922, p. 50) and Munthe's (1907; 1920, pp. 65, 108) somewhat diverging views seems to give as results a large oscillation after the uncovering of northeastern Zealand, a somewhat less fluctuation during the uncovering of central Zealand and southwestern Scania, and a third probably large oscillation (after the Alleröd period) when the ice-front retired in southeast Scania.¹ Besides, many minor oscillations were recorded by moraines, etc. Several of these are known to represent very long periods, many hundred years, or even more than 1,000 years. In all, the retreat must have taken many thousand years.

The recession from northern Germany may also have taken a long time. There are several belts of stadial moraines (Wahnschaffe and Schucht, 1921, pl. 29), and the retreat almost surely was very slow in the outermost zone of glaciation. So, the ice retreat from the terminal moraines up to central Scania probably took some 15,000 years or more. The shrinking of the last European ice-sheet then may have begun 25,000 to 30,000 or more years ago.

The post-glacial period in the Alps, according to Penck and to Brückner, (1909, p. 1169) began 20,000 years ago, in round figures.

The time since the ice left the Niagara Falls region, according to the latest estimate of the cutting of the Niagara gorge, which has occurred since then, is 20,000 to 30,000 or possibly 35,000 years (Taylor, 1913, p. 24). The time elapsed since the uncovering of Toronto, as estimated on the basis of the formation of the Iroquois shore, the recession of Scarborough Heights, Toronto, the building of Toronto Island, etc., is about 25,000 years (Coleman, 1914, p. 442; 1922, p. 71), and the time since the release from ice of Minneapolis, as estimated from the recession of St. Anthony Falls at Minneapolis, amounts to more than 12,000 (Sardeson, 1916, p. 13), according to an earlier estimate 30,000 years (Sardeson, 1908, p. 52). None of these estimates has reference to the whole time that has elapsed since the shrinking of the ice-sheet began, for all the localities lie far inside the terminal moraines.

The estimates in Europe and in North America, consequently, agree fairly well and make it almost certain that the ice-sheets disappeared at the

¹ Since the interstadial deposit at Robertsdal, 4 miles (6 km.) north of Ystad (Munthe, 1920, pp. 65, 127, 137), placed at the time preceding the low-Baltic ice-stream, lacks correlatives in Denmark, it may be wrongly dated. It may be an Alleröd bed. The mid-Baltic and the low-Baltic ice-streams in Scania and the probably corresponding southeast and south ice-streams in Zealand, consequently, may be separated by a relatively small fluctuation. Subsequent to the Alleröd period, the ice readvanced to Robertsdal, depositing a till bed, but probably did not go much farther.

same time on both sides of the Atlantic. In both cases the principal factor for the ice retreat seems to have been a rise in temperature (cf. p. 56). Therefore, when the ice recession shall have been chronologically studied in corresponding zones in both continents, as it is now in Sweden and in New England, agreement probably will be found between the large features of the ice retreat and climatic evolution in Europe and in North America. Times of decided retreat in Europe very probably will be found to correspond to recession in North America, and times of marked halts of the ice edge in the former continent to halts in the latter. In details, as in the annual recession, no agreement is to be expected. At present the summer temperatures in Scandinavia are largely opposite those in North America north of the Great Lakes (Hildebrandsson, 1910, plates 4 and 6; 1914). The annual temperatures in the two regions show little relationship (Mielke, 1913; Köppen, 1914). Furthermore, the ice recession was influenced by local conditions (cf. Antevs, 1922, pp. 68, 87). Dachnowski's (1922) attempt at correlation between Europe and North America can not be right, for, if there was correspondence, the ice recession in the United States on the whole must have corresponded to the retreat in Germany, and the uncovering of Canada to the release of Scandinavia.

From the almost certain contemporaneity of the disappearance of the European and North American ice-sheets, we can infer the contemporaneity of the last glaciations. Since the Tropics and the southern hemisphere also have suffered much more extensive glaciation in Pleistocene time than at present, it may be concluded that the glaciations in the different parts of the globe were contemporaneous and primarily brought about by conditions affecting the whole earth. This conclusion is corroborated by the probable correspondence also of the earlier Pleistocene glaciations in Europe and in North America, the degree of weathering of the deposits from the different glaciations in the two continents on the whole having been found to agree (Leverett, 1910; Leverett with Osborn and Reeds, 1922, p. 478). The corresponding extensions of the different glaciations in Europe and in North America speak for the same thing.

TEMPERATURE.

When summing up the great number of papers on the late-Pleistocene climate presented at the Eleventh International Geological Congress in Stockholm, 1910,¹ Gunnar Andersson (1912, p. 373) finds that all contributors except one, viz., Brockmann-Jerosch, see the chief cause of the Pleistocene glaciations in low temperature. This decision has particular weight, as the great majority of the best students of the subject stand behind it. The conclusion is drawn chiefly from the everywhere-existing indications of a lower temperature during the Ice Age than at present and from the dominating rôle played by the temperature also in the post-glacial climatic changes. The annual mean temperature in North Germany during the glaciations is thought by Gagel (1923, p. 32) to have been comparable to that now prevailing in West Greenland and in Spitsbergen; that is, is believed to have been 18° to 21.6° F. (10° to 12° C.) lower than at present.

¹ See *Die Veränderungen des Klimas, etc.*, and *Les changements du climat postglaciaire*, in the bibliography.

The factors bringing about glaciation, in all probability, were largely opposite to those causing its cessation. The studies by Gerard De Geer and his pupils of the shrinking of the last ice-sheets by means of the varved, or seasonally banded clays, which were deposited off the receding ice edge, seem to show that increased summer temperature was the principal factor for the waning of the ice (De Geer, 1910; see Antevis, 1922, p. 85). This suggests that the chief factor of the glaciation was low summer temperature.

Penck's and Brückner's (1909, p. 1146; Brückner, 1910, p. 106; 1912, p. 389) studies in the Alps, Machatschek's (1912, p. 101) in the westernmost Tian-Shan, and von Reinard's (1914, p. 107) in the Caucasus have led them to the same conclusion. The glaciations in these mountains were primarily brought about by a fall of temperature, particularly of that during summer. The depression of the snow-line in the Old World during the Ice Age indicates that the common great cause of each glaciation was low temperature (Machatschek, 1914, p. 125). Temperature also has a greater influence upon the altitude of the present snow-line than has precipitation (Paschinger, 1912, p. 86).

The consequences of low summer temperature were manifold, for it extended the frost season, caused a greater part of the precipitation to come in the form of snow, and prevented the complete melting of the snow during summer.

PRECIPITATION.

The importance of precipitation in solid form for deglaciation is difficult to estimate. During the shrinking of the ice-sheets precipitation seems to have been slight, probably much less than during their growth. If Simpson's (cf. p. 58) idea of the nourishment of the Antarctic ice-sheet is correct and can be applied to the Quaternary land ice, temperature played the decisive rôle in the precipitation over the ice, and the decrease of precipitation, when the ice-sheets had reached their greatest extension, may have been a consequence of a rise of temperature. In the rate of ice recession, the halts, etc., temperature played a greater rôle than did precipitation.

At present precipitation is abundant in many of the regions which were glaciated, and in these cases it does not seem necessary to assume a greater total quantity during the Ice Age. The precipitation in the Alps (Penck and Brückner, 1909, p. 1146), Tian-Shan (Machatschek, 1912, p. 101), and Caucasus (von Reinhard, 1914, p. 108) during glaciation appears to have equaled that at the present time. On the other hand, regions with slight precipitation, even if very cold, like Siberia for example, were and are not glaciated. It is beyond question that the growth of the huge Pleistocene ice-sheets required a considerable precipitation, and that in some glaciated regions this must have been heavier than now. Evidently it was so west of Hudson Bay, which region now is semiarid, and in Labrador, where now during the winter the very constant west and northwest winds bring hardly any precipitation, and the snowfall therefore only amounts to 3 to 6 feet (Low, 1896, p. 29). In the Great Basin the precipitation also was heavier, as will be discussed on page 73.

On the whole, therefore, precipitation may have been of somewhat less importance than temperature for the growth as well as for the shrinking of the Pleistocene ice-sheets.

NOURISHMENT OF AN ICE-SHEET.

The development of a continental glacier is little known. Chamberlin and Salisbury (1906, p. 356) think that the great Pleistocene ice-sheets formed a comparatively flat body with steep margins. The snowfall near the edge of the ice probably greatly exceeded that at the center of the ice-field, and an inframarginal belt rather than the geographic center may have controlled the marginal movements. This supposition is based upon the form of the existing continental glaciers and the difficulty of conceiving of an ice-sheet so thick at the center that it could reach such enormous size by expansion from the central parts. The authors referred to estimate that, assuming an average slope of 30 feet to a mile, the North American ice-sheet would have been more than 8 miles thick at the center in Canada, 1,500 miles from its outer edge in Illinois. This view is also corroborated by the fact that the great bulk of the till at any place is derived from the immediately proximal district. It is, however, significant that boulders were transported by the European ice-sheets from Dalarna and the Åland region, near the center of the glaciation down to the outermost limit of the glaciated area in central Europe (Milthers, 1909, p. 137, pl. I; see also Sederholm, 1911; Hausen, 1912, 1921; Wahnschaffe and Schucht, 1921, pp. 82-92). Nourishment in the center of the ice-sheets seems to have been great, perhaps as great as near the margins.

The meteorological conditions for the nourishment of an ice-sheet have recently been explained in different ways. Hobbs (1911, p. 287; 1911a, 1915, 1921), taking the Antarctic and Greenlandic ice-sheets as the two most pronounced examples, assumes the existence of an anticyclone over every extensive continental glacier. He thinks that the snow which falls in the central area is swept toward the edges of the ice-sheet by centrifugal currents of cooled air, which slides off the sloping ice, and is there deposited and consolidated into ice.

Meinardus (1911, p. 327), on the contrary, deduces that, in the Antarctic, the cyclonic type of pressure prevails over anticyclonic. He points out that in an anticyclone a precipitation large enough to nourish the huge ice-sheet is quite impossible; evaporation would exceed precipitation, and no ice would exist. The solution of the problem seems to be given by Simpson (1919, pp. 256-269; see also Wright and Priestly, 1922, pp. 8-11). Simpson finds that Hobbs in all probability is right in his opinion as to an anticyclone over the Antarctic. Simpson (1919, p. 265) continues:

"Owing to the anticyclonic conditions which predominate over the whole surface of the Antarctic, air flows toward the Antarctic in the upper atmosphere, then descends to the surface and there flows outward, at a much lower level than it entered. If the air were saturated at the moment it entered the Antarctic it would be warmed up dynamically as it descends and so when it reaches the surface it will be far from saturated. Even allowing for a large amount of radiation, air under these conditions could not deposit appreciable moisture on the surface and, as Meinardus points out, the conditions when precipitation is known to take place to the greatest extent, i. e., during cloudy weather and high winds, are exactly those when cooling by radiation is least effective. We have therefore to explain how air can enter the Antarctic in the upper atmosphere and leave it in the lower atmosphere and yet deposit moisture in the process."

An anticyclone in temperate and tropical regions produces dry weather for the following reason, says Simpson (1919, p. 267):

"The air enters the anticyclone in the upper atmosphere and descends toward the ground which has been made hot owing to the bright sunshine due to the absence of clouds. In

consequence the air in such an anticyclone on the whole receives more heat from the hot ground than it loses by radiation; it would therefore have to rise to a greater height than that where it entered the anticyclone before precipitation occurs. This is practically impossible, and therefore precipitation is of exceedingly rare occurrence in the anticyclones with which we are the most familiar.

"In the Antarctic, however, the conditions are reversed. It is only during a very short period of the year, and then only during parts of each day, that the air receives more heat than it radiates. This is shown by the tendency to form 'temperature inversions' near the ground which are especially well marked during the winter."

Precipitation may be obtained by raising the air which has descended to the ground.

"Such elevation of the air would result if a pressure distribution were imposed which set the surface air moving faster than the air in front of it; the air from behind would then be forced to rise over the air in front. This is the case during blizzards." (1919, p. 268.)

Simpson finds that formation of clouds precipitating snow occurs at heights of between 0.6 and 1.2 miles (1 and 2 km.), although this same air entered the Antarctic as a saturated current at an altitude of 3.7 miles (6 km.).

Simpson (1919, p. 268) sums up his view as follows:

"A statement of the general air circulation over the Antarctic is now quite simple. Over the snow-covered surface of the Antarctic, whether at sea-level or at the height of the plateau, radiation is so strong that the air is abnormally cooled, especially in the layers of air immediately above the surface. This cooled air is heavier than the surrounding air and therefore the pressure increases from the exterior to the interior of the Polar area; in other words, the pressure distribution is anticyclonic and the air motion is in general outwards. Above each anticyclone a cyclone forms on account of the relatively rapid vertical pressure change caused by the cold dense air. These cyclones convey air from higher latitudes over the polar region and supply the air which passes outwards near the surface. In the normal steady state the air circulation takes place slowly and the descending air is warmed up dynamically, so dissolving cloud and giving clear cloudless skies, thus accounting for the decreasing cloud amounts observed as one penetrates the Antarctic.

"The clear skies in their turn facilitate radiation, as also does the small absolute humidity of the air. In consequence the air and the snow surface become abnormally cold and there is a great tendency to the formation of temperature inversion, especially in the lower atmosphere. On these normal fine-weather conditions are superposed a series of pressure waves which travel more or less radially outward from the center of the continent. These waves alter the surface pressure distribution and cause air motion which is frequently, and especially over the west of the Barrier, accompanied by forced ascending currents. The abnormally cold surface air is forced upward in these currents, rapidly cooled in the ascent, and the water contained is precipitated as snow, which when combined with the high surface winds produces the typical Antarctic blizzard."

The generally accepted opinion of anticyclones above the Pleistocene ice-sheets, accordingly, seems to be correct.

The quantity of precipitation in the Antarctic anticyclone is unknown. According to Simpson (1919, p. 159) and Dines (1908, p. 47) it is totally impossible to form even an approximate idea about the amount of snowfall. Nor is it known in any other existing glacial anticyclone. Because of the great evaporation, it probably is not so slight as is supposed by some students. However, the existing ice-sheets are remnants from the Ice Age, and the two largest ones, the Antarctic and Greenlandic ice-shields, are probably shrinking instead of growing (Hobbs, 1911, p. 144). Located under relatively high latitudes and surrounded by cold seas, they furthermore are greatly favored over the large Pleistocene ice-sheets which extended southward to central Europe and to New York City respectively. They therefore can not be

taken as direct norms for the Quaternary land ice, which evidently required considerable precipitation.

The Antarctic ice seems essentially to be nourished by snow. Formation of hoar frost in Meinardus's (1911, p. 328) mind is not worthy of mentioning. At great altitude in the Swedish mountains, however, formation of hoar frost is very considerable (Hamberg, 1907). Brooks (1922, p. 28) thinks there is little true snowfall on the ice-sheets, but that the condensation takes place chiefly close to the surface, forming a frozen mist resembling the "ice-mist" of Siberia.

In the Antarctic the fallen snow is carried along in the air and does not settle, except in the lee of any obstacle (Simpson, 1919, p. 159). Since the prevailing winds are centrifugal, the snow is transported toward the margins of the ice-sheet. As pointed out on page 57, however, a large part of the precipitation must have become consolidated in the central regions of the Pleistocene ice-sheets, at least of that in Europe.

To a noteworthy degree the ice-sheets, as Huntington and Visser (1922, pp. 116, 125, 136) point out, may have been nourished by snowfall from cyclonic storms near their margins.

PRECIPITATION OUTSIDE THE PLEISTOCENE ICE-SHEETS DURING THEIR GROWTH.

The amount of precipitation in the unglaciated parts of the earth during the growth of the ice-sheets seems to be practically unknown. While the great windiness which must have been a consequence of the strengthened gradient of temperature from the Equator poleward tended to increase evaporation, the low temperature worked in the opposite direction. Other conditions may have influenced evaporation somewhat, essentially diminishing it. The net result of these controversial influences can not very well be estimated, but the total evaporation probably was not greater than at present.

Since the precipitation in some glaciated areas was considerably heavier than in our time, and moisture consequently must have been transported from low to high latitudes as also pointed out by Huntington and Visser (1922, p. 118), it is likely that the unglaciated regions received less precipitation than they do to-day.

GREAT CLIMATIC CHANGE ENDING EXPANSION AND CAUSING SHRINKING OF THE ICE-SHEETS. THE PLUVIAL PERIOD.

When the last ice-sheets had reached their greatest extension, and had expanded to central Europe and New York City respectively, the most remarkable change of the climate during late-Pleistocene time occurred. The factors tending to increase the ice-sheets were now counterbalanced by the factors working on their destruction, and the land ice ceased to grow. For many hundred years an undecided struggle went on, until finally shrinking of the ice-sheets began. At first the rate of retreat of the ice edge seems to have been very slow and repeatedly interrupted by halts and readvances, but on the whole it increased (cf. p. 62). The ice retreat, as already pointed out, may primarily have been brought about by a rise of temperature, particularly of the summer temperature. The amelioration increased ice melting and shortened the frost period which in its turn reduced the snowfall. Indirectly

it also had another great effect, if Simpson's view of the meteorological conditions of precipitation in the Antarctic can be applied to the Pleistocene ice-sheets (cf. p. 58). For in Simpson's opinion low temperature near the ground is the most essential thing for precipitation in an anticyclone, and consequently the rise in temperature reduced or prevented the precipitation of moisture on the ice-sheets.

Also, off the ice edge precipitation was slight. During most of the glaciation, and so during its maximum extension, the districts outside the ice-sheets seem to have had the character of arid tundras, inhabited by arctic to subarctic floras and faunas (Nathorst, 1914; Weber, 1914; Soergel, 1921, p. 45; Gagel, 1923; Range, 1923). When the ice edge began to retreat, it was followed by this tundra or *Dryas* belt. Outside this zone, during the first time of the last ice recession in Europe, there perhaps lay a steppe belt (Andersson, 1910, p. xxxvii; Stoller with Wahnschaffe, 1910, p. 14). A steppe zone perhaps represented every ice recession under certain conditions. In so far as the loess deposits, connected with the Pleistocene glaciations, really were formed during the shrinking of the ice-sheets, they also indicate dry climate off the ice. In Europe, however, little loess seems to have been deposited since the maximum of the last glaciation (Andersson, 1910, p. xxxvii; Wright, 1914, pp. 210-212; Brückner, 1919). In North America, loess overlies late Wisconsin drift in places, though this usually is free from it (Chamberlin and Salisbury, 1906, p. 408). Its nature as well as its molluscan fauna indicate a climate somewhat drier than that at present (Alden, 1910, p. 358). A climate with very warm and dry summers now exists in West Greenland between the sixty-fourth and sixty-ninth parallels, close to the edge of the continental glacier (Nordenskjöld, 1916, pp. 39, 41).

In short, the end of expansion and the retreat of the ice-sheets were connected with increase in temperature and decrease in precipitation in the glaciated areas. The rise of temperature probably increased evaporation, which must have been considerable, since a strong windiness still persisted during the ice retreat. These conditions, more or less pronounced, evidently followed each glaciation.

The changes in the meteorological conditions in the northern part of the northern hemisphere caused by the expansion of the ice-sheets are perhaps best shown by Enquist (1916, p. 100, plate 2). As mentioned, in all probability high air-pressure permanently prevailed over the ice-sheets. During the greatest extension of the glaciation the present low-pressure area around Iceland was pushed down to the southern part of the North Atlantic, to the region now occupied by the Azores high. This cyclone also influenced the European peninsulas in the Mediterranean, North Africa, Asia Minor, Syria, Mesopotamia, northern Arabia, Persia, and neighboring regions to the north and east. It might have extended westward over the southern United States. The cyclone which now occurs in winter over the northernmost portion of the Pacific Ocean was much more strongly developed and perhaps reached over the Great Basin, where it possibly met the Atlantic low just mentioned. Since the anticyclones over the ice were permanent, these lows also must have been permanent. In these low-pressure regions the deficit of precipitation over and near the shrinking ice probably was made up. Since the lows brought rains throughout the year, these regions had a pluvial

period; now they have little or practically no summer rains and are to a large part occupied by steppes, semideserts, and deserts.

Not the whole of the present arid or semiarid belt referred to had a pluvial climate, but as Hume and Craig (1911) and Penck (1913, p. 89) point out, the dry zone was pushed toward the Equator. The Pleistocene lakes in the Basin-and-Range province were crowded in the northern portion and scarce in the southern part, indicating decreasing humidity southward (Meinzer, 1922, p. 544; cf. p. 71).

The occurrence of *Rhododendron ponticum* in calcareous tufa in the island of Skyros in Greece is conclusive evidence of a heavier precipitation during the vegetative period than at present (Andersson, 1910a, p. 149). In Africa only the northern part of the present desert belt was influenced; south of the twenty-fifth parallel of latitude in Egypt all traces of a pluvial period are lacking (Blanckenhorn, 1910, p. 428). Over Abyssinia, on the contrary, the precipitation was reduced, and the Abyssinian Nile system did not reach Egypt (Hume and Craig, 1911).

Somewhat more than 14,000 years ago, as estimated by the thickness of the alluvial muds at Cairo, i. e., during the last glaciation, the climate in northeast Africa, according to Hume and Craig (1911), was moister and several degrees colder than now (cf. Hume, 1910; see also Beadnell, 1909; Huntington, 1910; Brooks, 1914, p. 63). Also, in western Asia the climate seems to have been moister during the last glaciation, as indicated by different writers and especially by Huntington, in a number of papers (see Huntington and Visser, 1922, p. 143). Lately Blanckenhorn (1921a, pp. 10, 11), abandoning his old opinion that the two last glaciations had little influence upon the humidity of Egypt, Palestine, and Syria, distinguishes a pluvial period for each glacial period. The first three pluvials were progressively marked; they are together called the great pluvial. The fourth pluvial period, corresponding to the last glaciation, was least pronounced and is called the little pluvial.

On the other hand Machatschek (1912, pp. 100, 133) believes that the maximum extension of the Aralocaspian Sea preceded the last glaciation, during which the distribution of water and land in the Turanic lowland was about the same as now. He also thinks (1912, pp. 99, 101; 1914, p. 376) that the glaciations in the western Tian-Shan were brought about by fall in temperature and that the large extensions of the Aralocaspian Sea were a consequence of little evaporation because of low temperature and not a consequence of heavy precipitation. During the glaciation the prevailing winter winds in Turkestan and the Tian-Shan came from the east and northeast, from cold and dry Siberia, and caused little snowfall. During summer the Aralocaspian Sea caused the formation of a secondary high off the permanent high-pressure area over the European ice-sheet. It probably was surrounded by lows, and the distribution of the atmospheric pressure and winds was like that now existing over the eastern Mediterranean. The winds in western Turkestan must have come from the north-northwest and northwest, and summers must have been dry. These conditions, however, have reference to the maximum extension of the ice. When the temperature rose and the ice-edge began to retire, the rainfall might have essentially increased without markedly affecting the development of the glaciation in the neighboring mountains. As the ice-sheets diminished, the climatic conditions gradually changed in the direction of those now prevailing.

II. EVOLUTION OF CLIMATE IN LATE-GLACIAL AND POST-GLACIAL TIME.

NORTH EUROPE.

As shown in the above analysis of the climatic conditions during the height of glaciation, the pluvial periods almost certainly corresponded to the largest expansion of ice-sheets and the early days of ice recession. A short review of the evolution of the climate in a few representative regions during late-glacial and post-glacial time will make this supposition still more probable.

The climate during the uncovering of Germany and Denmark has already been somewhat touched on on pages 54 and 60. In Germany the rate of ice recession, which is unknown, probably was very slow, since a series of stadial moraines indicates repeated halts and readvances of the ice-edge (Wahn-schaffe and Schucht, 1821, plate 29). The receding ice border was followed by an arid tundra belt, characterized by a *Dryas* flora. Outside this belt, in the outermost zone of the glaciated area, there perhaps lay a steppe belt. The amelioration of the climate, consequently, was slow, not very great, and subject to several reversals.

The climate during the uncovering of the Danish Islands and southwestern Scania underwent very noteworthy changes, as may be inferred from the repeated large oscillations of the ice-border and the many and long halts in the retreat (cf. p. 54). Close to the ice-edge it was arctic, as plants embedded in the varved clays testify. When the ice had definitively withdrawn from Denmark, Bornholm, and southwestern Scania, and probably had retired beyond the northwest-southeast diagonal of the last-named province, a marked temperature rise in the southwestern region of the Baltic occurred. This mild time, known as the Alleröd period, is recorded by about 25 known occurrences of fossiliferous beds distributed all over the area from Scania and Bornholm to Jutland and Holstein (see Nordmann, 1910, pp. 315-319, 325; 1915, 1922). The Alleröd beds are fresh-water deposits and consist largely of marl or calcareous gyttja.¹ They contain a flora and fauna indicative of a temperate continental climate. The actual climate has been much debated. Different students think that the shallow ponds in which the mollusks lived were abnormally heated by insolation during summer, so that their temperatures were essentially higher than that of the air. A probably similar typically continental climate with very dry and abnormally warm (54° to 59° F. = 12° to 15° C.) summers is described by Nordenskjöld (1916, p. 39) from West Greenland, between the sixty-fourth and sixty-ninth parallels, from the immediate neighborhood of the continental glacier, but some 80 miles (130 km.) from the open sea. Subsequent to this mild period the climate again grew colder, for the Alleröd beds are regularly overlain by clays containing arctic plants. These top clays, in distinction from the underlying clays which also contain arctic plants, are not varved; they were not

¹ Gyttja is a sediment largely consisting of remains of plants and animals, as vascular plants, algæ, crustaceans, mollusks, etc., and of excrements.

deposited immediately off the ice-edge.¹ The ice-front may have readvanced over central and southeast Scania, but not farther.

The following retreat appears soon to have been interrupted by a long halt, for a local clay deposit at Rörum, 6 miles (10 km.) north-northwest of Simrishamn, whose formation postulates ice-damming, contains about 1,500 annual layers. This clay deposit is typical of a halt of the ice-border caused by little melting and is very different from the clays formed during the annual retreat of about 300 feet (90 meters) in northeast Scania, with which they have been tentatively connected by De Geer (1917, p. 243).

Subsequently, a marked amelioration of the climate set in, and the waning of the ice, though interrupted for shorter periods of time, started in earnest. In Sweden, the rate of the ice retreat from the south coast of Blekinge (56° N.) to Ragunda (63° N.) in Norrland (450 miles or 720 km., in 4,000 years) averaged about 600 feet (180 meters) a year (De Geer, 1912, 1914). In the southern part, from Blekinge to the Fenno-Scandian moraines (150 miles or 240 km., in 2,000 years), the annual recession amounted to 400 feet (120 meters), and in the northern part, from the moraines up to Ragunda (280 miles or 450 km., in 1,500 years) to 1,000 feet (300 meters). The morainic belt represents two halts and slow intervening recession for a total of nearly 700 years (Sauramo, 1918, p. 23). The almost catastrophic rapidity of the decay of the ice in central and northern Fenno-Scandia is, by Enquist (1918, p. 107), connected with the possible breaking in of the Gulf Stream into the Norwegian Sea as a consequence of lowering of the Wyville-Thomson Ridge.

The dry arctic to subarctic belt followed the receding ice border up to central Sweden (see Antevis, 1922, p. 90). As a consequence of the anti-cyclone over the remnant of ice and the resulting northeasterly and easterly winds, the subsequent climatic belt or the boreal belt, in Sweden, to which the following refers, was characterized by dry summers, during which the lakes sank considerably, but rather mild winters which were rich in precipitation (von Post, 1920, pp. 235-237, 240). The climate on the whole was maritime, not continental as previously supposed; it somewhat suggested the Mediterranean type. The relationship between the changes of level in northern Europe and the continental and maritime climates respectively during late-glacial and early post-glacial time is not known, the opinions on the changes of level disagreeing (Antevis, 1922a; Munthe, 1924; cf. Brooks, 1917, 1921; 1922, p. 120).

As influence of the ice remnant diminished, the summer drought decreased, and as the land underwent a subsidence, the Tapes-Littorina submergence, during which the Gulf Stream for the only time washed the Swedish west coast (Andersson, 1910b, p. 293), the climate became typically maritime. This is the Atlantic period. As the land rose to its present position, the climate gradually changed to decidedly continental, the subboreal period, with slight summer precipitation, causing a great number of lakes to fall below their outlets.

¹The overlying clays at Stenstrup in Fyn, as the Danish geologists maintain, and as this writer observed in 1919, on the whole show but obscure lamination, as may any water-laid deposit, not a lamination comparable to that of the varved late-glacial clays. Only in one of the clay-pits a zone about 1.5 feet (0.5 meter) thick showed fairly distinct lamination which probably is seasonal. It would, however, be hasty to conclude that the ice-front stood in the neighborhood when the clay was deposited, for other conditions seem convincingly to prove that it stood far away.

The amelioration proceeded since late-glacial time, and the post-glacial temperature maximum probably was reached during sub-boreal time, from about 5,500 to 2,500 years ago, as best shown by Sernander's (1910, p. 245; 1912, p. 405), von Post's (1909, 1916), and Sandegren's (1915, plate 4) excellent stratigraphic and paleontologic studies of peat-bogs and other deposits, and also indicated by the marine molluscan fauna on the Swedish west coast (Antevs, 1917, p. 269). The temperature during mid-summer, according to a conservative estimate was then 2.7° F. (1.5° C.) higher and the vegetative period about 15 days longer than at present, as especially shown by the distribution of many plants far north of their present occurrence (Samuelsson, 1915, p. 112). With the beginning of the Iron Age, or a few hundred years B. C., a very rapid drop in temperature occurred, to below the temperature now prevailing, to which it has gradually risen. This period, the sub-Atlantic period, is also characterized by a moist climate, particularly in the earlier part.

The warmth maximum, according to Andersson (1910*b*, p. 292; 1912*a*, p. 152), prevailed during Atlantic time from 6,000 or 7,000 to about 4,000 years ago. The subsequent fall of temperature in the beginning was rather rapid, then very gradual, till the present conditions were reached. The highest summer temperature, as far as the testimony of the swamp flora goes, in Sundelin's (1919, p. 236) mind, fell in the later part of boreal or Ancylus time. In noteworthy correspondence with this the temperature of the sea on the Swedish west coast, as recorded by the molluscan fauna, seems to have reached a secondary maximum before the greatest Tapes submergence (Antevs, 1917, p. 269).¹

In historic time the climate in northern Europe has undergone fluctuations of long and short duration, but not really changed for better or worse (Pettersson, 1912; Norlind, 1914, 1915; Speerschneider, 1915; Hildebrandsson, 1915, 1916; Ward, 1918; Huntington and Visher, 1922, pp. 98-107; Brooks, 1922). During the fourteenth century several winters were remarkably cold, so that the entire Baltic and the rivers in central Europe were frozen over. The cold winters, on the continent, were followed by violent floods in the rivers. The climatic stress also expressed itself in destructive storm-floods on the coasts of the Baltic and the North Sea, as well as in other ways.

NORTH AMERICA.

The climatic conditions in North America in late-glacial time are partly revealed by the ice recession, which was primarily determined by temperature. In the outermost zone of the glaciated area the recession was very slow and frequently interrupted by halts and readvances. The deep, thinly varved clays south of Hackensack, New Jersey, record a few thousand years. In New England the ice recession, though interrupted sometimes, averaged 22 years to a mile (1.6 km.) or 238 feet (72 meters) a year (Antevs, 1922, p. 74). In northern New England the rate reached more than 1,000 feet (300 meters) annually. The temperature, accordingly, from being rather low during the uncovering of the marginal zone, rose gradually, in spite of several reversals.

¹ von Post (1924) and Sandegren (1924, pp. 43, 52), in papers that came too late into my hands to be considered, now hold that the temperature maximum was reached in atlantic time and prevailed from about 7,000 years ago to 3,500 or 2,500 years ago.

The climate during the ice recession in New England was not arctic, though a zone with an arctic to subarctic flora and fauna followed the retreating ice-edge (cf. Gleason, 1922, p. 22). In Massachusetts such a flora was found in the varved clay (Emerson, 1889, p. 718; cf. Antevs, 1922, p. 89). On the east coast of New England and of Canada, as well as in the Champlain Sea lived a molluscan fauna indicative of a temperature similar to that off Labrador at the present time (Dall, 1910; Matthew, 1910, p. 377; Johnston, 1917, p. 28; Goldring, 1922). Fossil reindeer are found at seven localities south of the forty-second parallel (Hay, 1910, p. 372). Mastodons and mammoths were frequent in New York State during the waning of the ice (Hartnagel and Bishop, 1922). As the ice shrank the climate changed from subarctic to cold temperate, as shown by the upper Leda clay in the Fundy Bay region (Matthew, 1910, p. 378), by subfossil beaver, caribou, *Larix americana*, etc., in the Ontario Basin (Coleman, 1910, p. 386; 1922, p. 49), and by a rich fossil flora and mollusk fauna at Chicago (F. C. Baker, 1920, p. 194). During the Algonquin and the Nipissing Great Lakes stages the temperature, as recorded by the molluscan fauna of the lakes, appears to have been about the same as at present (Johnston, 1916, p. 16; Coleman, 1922, pp. 34, 38). In Saskatchewan and adjacent provinces the cold climate was succeeded by a warmer continental climate, under neither of which conditions was a forest growth possible (Tyrrell, 1910, p. 390).

The climatic amelioration proceeded, and finally, in the northeastern part of the continent, the climate became even milder than to-day. Hence the marine mollusks *Ostrea virginiana* var. *borealis* and *Venus mercenaria*, whose present northern limit of distribution is Cape Cod, once were spread up to Casco Bay in Maine (Matthew, 1910, p. 378). Subfossil marine shells at Boston indicate a climate similar to that off the Virginia coast at present (Shimer, 1915, 1918). A fish-weir found in the deposit shows that man lived in the region during the warm period, which may lie 2,000 to 3,000 years back in time. Subfossil fresh-water shells in the gravels of the Niagara River perhaps also speak of a higher temperature a few thousand years ago (Coleman, 1910, p. 386; 1922, p. 40). Different plants in the Eastern States once reached farther north than they do at present (Knowlton, 1910, p. 369; F. C. Baker, 1920, p. 194). The earlier distribution of various mammals makes it probable that the southern shores of Lakes Ontario, Erie, and Michigan enjoyed a climate comparable to that now prevailing in Tennessee and Arkansas (Hay, 1910, p. 374; cf. F. C. Baker, 1920, p. 194).

Composition and stratigraphy of peat-bogs in Ohio seem to indicate alternation of dry and humid periods since the disappearance of the ice-sheet (Dachnowski, 1921, p. 85; 1922, p. 226).

The late-Pleistocene climatic evolution in North America, consequently, in many respects seems to have run parallel to that in Northwest Europe. As knowledge grows the correspondence, in all probability, will be found greater. Particularly noteworthy is the fact that the post-glacial maximum of temperature was fairly certainly contemporaneous in both continents.

In the Southwest the moisture in post-glacial and recent times has undergone perceivable changes, as recorded by oscillations of the levels of many lakes and changes in civilization (Huntington, 1914a, 1922a). Thus, Owens Lake, California, overflowed 4,000 years ago or later (Gale, 1914, p. 264).

Pyramid Lake, Nevada, perhaps also overflowed a few thousand years ago, or contemporaneously with Owens Lake, while Walker Lake and perhaps also Winnemucca Lake, Nevada, have been dry at a later date (cf. p. 102).

The varying width of the growth-rings of the big tree, *Sequoia washingtoniana*, in the Sierra Nevada, also indicates fluctuations, not of a single climatic factor, but of a combination of factors, among which temperature, precipitation, and sun radiation appear to be most important (Antevs, 1925). It is particularly noteworthy that exceptionally wide annual rings were formed contemporaneously with the climatic stress during the fourteenth century known by historical records in the Old World (cf. p. 64). Correlation between rate of growth of the Big Tree and fluctuations of the lakes in the arid regions in the western States should be avoided, until the conditions governing the growth of the sequoia are better known, and the datings of the lake fluctuations are more accurate.

MEDITERRANEAN REGION AND WESTERN ASIA.

When the greater part of the ice-sheet in northern Europe had disappeared, the permanent low which had supplied the Mediterranean region and western Asia with a relatively abundant summer precipitation moved northward. Hence, the extraordinary climatic conditions, caused by the glaciation, gradually and probably under fluctuations changed into those now prevailing. The present-day conditions, according to most students of the subject, were reached early in post-glacial time, and since then no marked change has occurred (Leiter, 1909; Hume, 1910; Blanckenhorn, 1910a; Berg, 1914; Gregory, 1914; Hildebrandsson, 1915, 1916; Ward, 1918). In Persia a progressive desiccation has occurred since the glacial period (Hedin, 1910). High culture and large population in now arid, unfertile lands, irrigation ditches and lake strands in regions now without water, etc., are explained in one way or another without accepting variations of the climate. However, the most natural and direct explanations seem not always to have been given, and so the view of distinct climatic fluctuations, advanced especially by Huntington in a number of papers (see Huntington and Visher, 1922, pp. 64-97) is being more and more accepted (Butler, 1920; Brooks, 1922, pp. 149-158). The very best evidence of the occurrence of climatic fluctuations of short as well as of long duration, up to thousands of years, is probably to be found in the varying rate of the radial growth of the big tree and in the periodic retreat and halt of the edge of the Pleistocene ice-sheets (Huntington, 1914a; Antevs, 1922, pp. 74-93; 1925). Huntington shows that there have been during historic time, within limited regions, climatic fluctuations of different length and character, but particularly in precipitation. The most noteworthy fact is that, especially in western and central Asia, the climate 2,000 or 3,000 years ago appears to have been distinctly moister than to-day.

III. GLACIATIONS IN THE GREAT BASIN.

After the preceding short treatment of the chief factors and conditions of glaciation and of the evolution of climate in late-Pleistocene time, necessary for the understanding of the relationship between glaciations and pluvial periods and for the dating of these latter, we turn to the Great Basin.

Several of the loftiest mountains in the Great Basin region suffered glaciation in Pleistocene time, but most of them only to a small degree. The glaciations, in the final analysis, were caused by the same factors as were the ice-sheets in the northeastern part of the continent, but in detail they were essentially a result of conditions brought about by the expansion of these ice-sheets. The glaciations in this region, therefore, began shortly before the ice-sheets reached their maximum extension.

So far, three Quaternary glacial epochs are known from the southwestern part of the United States, viz, in the San Juan Mountains in Colorado (Atwood and Mather, 1912). In the Great Basin region only two glaciations are yet known with certainty, though outlying boulder deposits in the Uinta Mountains, recognized by Atwood, suggest a third and earlier glacial epoch, probably corresponding to the earliest one in the San Juan Mountains (Atwood and Mather, 1912, p. 409). Pack (1922), in passing, speaks of three well-defined glaciations in Utah.

The degree of weathering, of erosion, etc., shows that the glaciations in the different mountain ranges were contemporaneous (Atwood, 1909; 1912, p. 408; 1916, p. 719). There is, as Atwood (1912, p. 387) points out, no way of directly correlating the glacial epochs among the mountains with the great ice-sheets, but what we know about the glaciations, their causes, conditions, and consequences, invariably speaks for their contemporaneity.

From a climatologic point of view we can even expect a glaciation in the western mountains corresponding to each ice-sheet. On the other hand, the idea that the glaciations in the two regions would be of different dates is absurd.

The moraines from the last glaciation in the Wasatch and Uinta Mountains, as well as in the Sierra Nevada, are only slightly weathered or almost fresh in appearance (Atwood, 1909, pp. 78, 69; Russell, 1889, p. 389). The moraines of the next to the last glaciation in the Wasatch Mountains and in the Sierra Nevada are considerably weathered, so that many stones can be crushed between the fingers (Atwood, 1909, pp. 78, 81; Russell, 1889, p. 389), while the moraines in the Uinta Mountains are almost as fresh as those of the last glaciation, because of being composed of very hard quartzite (Atwood, 1909, p. 68). The degree of weathering of the earlier moraines shows that the interglacial epoch was much longer than the post-glacial time.

The northeastern part of North America during the Pleistocene was covered by continental glaciers four or five times (Leverett, with Osborn and Reeds, 1922, p. 478). Since the different ice-sheets were caused largely by the same conditions and reached approximately the same extension, each one of them, as already stated, ought to have corresponded

with glaciation in the Great Basin region, though so far only three are known here. But the deposits from an earlier glaciation were almost completely torn up or covered by deposits during the next expansion of the ice; but if the earlier glaciation was more extensive than the later ice, more abundant and recognizable records of it are sure to remain.

It seems to be beyond doubt that the youngest moraines in the western mountains correspond to the last ice-sheet. It is also very probable that the next to the youngest moraines correspond to the next to the last glaciation, and the oldest moraines to the Kansan glaciation, which was most extensive.

The extension of the earlier glaciations is little known, so that the following has reference to the last glaciation only. In the Bonneville drainage area the highest parts of the Wasatch and Uinta Mountains and Belknap Peak, 165 miles south of Salt Lake City, were glaciated (Gilbert, 1890, plate 49, p. 374; Atwood, 1909). Of the Uinta glaciation only about the western quarter belonged to the Bonneville drainage area. The detailed mapping of the Wasatch and Uinta glaciations by Atwood brings forth several interesting facts. The elevation of the catchment basins in the Wasatch Mountains was nearly 9,000 feet. Among the glaciers in the mountain range southeast of Salt Lake City 50 exceeded a mile in length, 10 exceeded 5 miles, and 1 reached 12 miles; 7 glaciers descended to the altitude of 5,000 feet, i. e., to the level of the shore-line of Lake Bonneville.

Of the Uinta Mountains, by far the greater part west of longitude 109° 40' west was covered by ice (Atwood, 1909, p. 65). The glaciated area measured 82 miles in an east-west direction and 42 miles north and south. The glaciation was much heavier on the southern side than on the northern, indicating, according to Enquist (1916, p. 56), prevailing northerly, or, more precisely, northwesterly winds. The necessary altitude of the catchment areas was about 10,000 feet.

In the Lahontan drainage area the highest portions of the Sierra Nevada and the East Humboldt Range were glaciated, and the loftiest peaks of the Shoshone, Star Peak, and Granite Ranges were crowned by small ice-caps (King, 1878, plate 5, p. 486; Russell, 1885, p. 266; 1889, p. 327). In the Sierra Nevada the glaciation was considerable, though not so extensive as was supposed after the preliminary studies. The range was not domed over by a continuous ice-sheet; it was rather glaciated against its upper slopes (Johnson, 1904, p. 572). The summit tracts were bare.

The Quaternary glaciation in the Mono drainage area and adjacent parts of the High Sierra, as shown by Russell (1889, plate 29, p. 329), was considerable. All canyons of importance contained ice-tongues, the largest of which descended into the valley below the highest shore-line of the Pleistocene Lake Mono at 7,060 feet altitude.

IV. METEOROLOGICAL CONDITIONS IN THE GREAT BASIN.

AT THE PRESENT TIME.

It is a commonly known fact that the whole Great Basin at the present time is arid and occupied by deserts, because the prevailing southwest winds have precipitated the greater part of their moisture during the ascent of the high Sierra Nevada and, furthermore, through heating during the following descent have increased their capacity of retaining moisture, so that they cause much greater evaporation than precipitation. The moisture contained in the air after passing the basin is largely precipitated in the highest portions of the Wasatch, Rockies, and other mountain ranges to the east. To some extent the precipitation in the basin region is caused by passing cyclonic storms. Therefore the basins and valleys in the area depend for their water on the precipitation in the high mountains. The data used below, when no source is given, are essentially taken from the latest Summary of the Climatological Data for the United States, but also from McAdie (1903, 1914), Jefferson (1916), Ward (1917), and Kincer (1922).

Striking features, besides the dryness of the air, are the clear sky, the bright sunshine from March to October, and the exceedingly large diurnal range of temperature. Even after intensely hot days of about 100° F. (38° C.) the nights are quite cool. The mean diurnal range, at some places, amounts to about 40° F. (22° C.). The winters are cold. Temperatures below Fahrenheit zero (−18° C.) are recorded from almost all parts.

The precipitation in western Utah is comparatively slight, ranging from 6 to 25 inches annually and averaging about 13.5 inches. It is heaviest in the eastern, high parts of the Wasatch Mountains and diminishes toward the west, where it varies greatly according to elevation. In the flatter western districts it is slight, the chief governing factors being altitude and distance from the mountains. The western slopes of the mountains receive more precipitation than the eastern slopes. The precipitation is fairly well distributed over the year, but on the whole is heaviest in the winter and spring months. June to September are relatively dry, except in the southernmost part where a secondary summer maximum is reached. At some stations August is even the wettest month of the year.

The annual mean evaporation from Great Salt Lake and free water-surfaces in the district is probably between 45 and 55 inches.

Practically all the streams discharging into the Bonneville Basin come from the Wasatch and Uinta Mountains, on its eastern side, and are fed by melting snow or by springs. The annual high-water period occurs in May and June. Now many of the streams are used for irrigation, so that they are exhausted at least for part of the year.

The amount of precipitation in the Lahontan drainage area varies greatly, according to distance from the Sierra Nevada, altitude, and situation with reference to the prevailing rain-bearing winds, but averages about 9.5 inches annually. It is greatest on the slopes of the Sierra Nevada and decreases

from the crest eastward. Relatively heavy precipitation also occurs in the high mountain ranges in the central and eastern part of Nevada. The annual mean precipitation at Summit, in the Sierra, west of Reno, is 46.99 inches, at Reno 8.50, and at Fernly, east of Reno, 4.73 inches. In practically the whole of the Lahontan Basin the rainfall is less than 10 inches, and in a great part of it less than 5 inches. Of the annual precipitation more than one-half falls in the 4 months from December to March, and over three-fourths in the 7 months from November to May. In the highest parts of the Sierra the heavy precipitation is strikingly concentrated in the winter months, and comes mostly in the form of snow. At Summit the mean snowfall is 441.6 inches. In the foothills and valleys much of the winter precipitation is rain. The summers are hot and exceedingly dry and sunny, and as a consequence the evaporation is very great, amounting during the months from April to September to about 51 inches.

The rivers of the basin rise in the high mountains on its western and eastern borders and receive their principal supply from melting snow which fell during the winter months. The maximum discharge occurs in late spring or early summer, after which the flow decreases, reaching a minimum during winter. After leaving the mountains the rivers get little increment, but instead lose through evaporation and seepage, so that they often entirely cease to flow.

The chief rivers come from the Sierra Nevada. The Humboldt River rises in mountain ranges in the northeastern part of Nevada and flows west and southwest. During low stages the water of the river is almost entirely diverted. The Quinn River, rising in the northern part of the basin, loses itself in the Black Rock Desert.

For the Mono Basin, which also is a desert, no meteorological records exist. At Bodie, lying just outside the northern limit of the basin, the annual precipitation is about 14 inches, of which the greater part comes during the months November to April inclusive. In the Sierra Nevada, bordering the basin on the west, the precipitation is much greater and increases toward the crest, where it may be somewhat less than 40 inches. The greater part of it comes during the winter months. From June to August the rainfall in the high Sierra, as well as in the Mono Valley, is less than 3 inches. At elevations under 7,000 feet the snow disappears, and the ground is bare during July, August, and September. The summits of many peaks are snowclad throughout the year.

The principal source of water-supply of the Mono Basin, besides springs, consequently, is the high Sierra, from which several creeks descend to Lake Mono at the foot of the mountain range. The lake has not overflowed in mid-Pleistocene (?) and late-Pleistocene time, but the water which the creeks bring down evaporates, so that the lake keeps an approximately constant level. Along the shore, however, there are drowned trees, brush, and fences, and, according to information, the lake-level has risen about 30 feet in the last 25 years. The trees were reached by the rising lake in 1914. One of them has been found to be nearly 150 years old, showing that the highly alkaline lake, which soon kills off all vegetation with which it comes in contact, had not stood so high for this period of time (Huntington, 1917, p. 156). Since some water is lost by irrigation, the climate within the drainage area must have become somewhat moister in recent times.

DURING THE GLACIAL EPOCH.

As will be shown in a later chapter, the expansions of the Pleistocene lakes in the Great Basin corresponded to the maximum extensions of the glaciations in the neighboring mountain ranges and the ice-sheets over the northern part of the continent.

According to Meinzer's (1922) recent study the Basin-and-Range physiographic province, which extends in the United States from southern Oregon to trans-Pecos Texas, contains 125 basins without surface outlets for the water that falls upon them. In this province there were 68 or probably a few more Pleistocene lakes, the distribution and size of which are seen from map below.

"The northern part of the province was crowded with Pleistocene lakes, most of them of good size; farther south the lakes were smaller and less abundant, and some large basins contained no lakes of sufficient size and permanence to leave distinct shore features. In southwestern Arizona lakes were absent, because there were no closed basins that could hold lakes, but in southeastern California and trans-Pecos Texas closed basins occurred, and the absence or scarcity of lakes in these parts of the province was apparently due to aridity." (Meinzer, 1922, p. 544.)

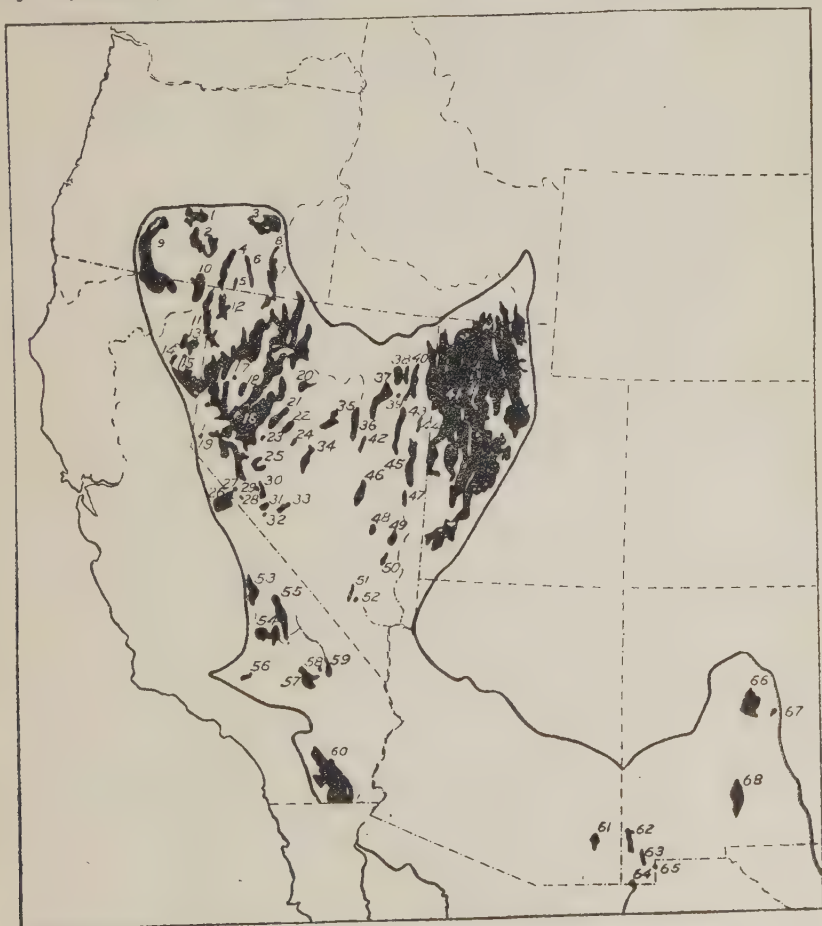


FIG. 1.—Map of the Pleistocene lakes in the Basin-and-Range Province. No. 16 is Lake Lahontan, 26 is Mono, and 41 Bonneville.

(From Bull. Geol. Soc. of America, vol. 33, 1922, by O. E. Meinzer.)

Hence, the difference in humidity between the northern and southern parts of the province in Pleistocene time was greater than at present, the existing southward increase in the rate of evaporation and decrease in precipitation then being accentuated.

The two major lakes, Lake Bonneville in Utah and Lake Lahontan in Nevada, were essentially fed by streams which even now are perennial and most of which rise in the lofty Wasatch Mountains and the Sierra Nevada, respectively.

"Lake Bonneville occupied 38 per cent of its basin, and then overflowed. Lake Lahontan occupied about 20 per cent of its basin, the smaller percentage being due largely to the extensive area of relatively unproductive country east of the lake that was included in its drainage basin." (Meinzer, 1922, p. 544.)

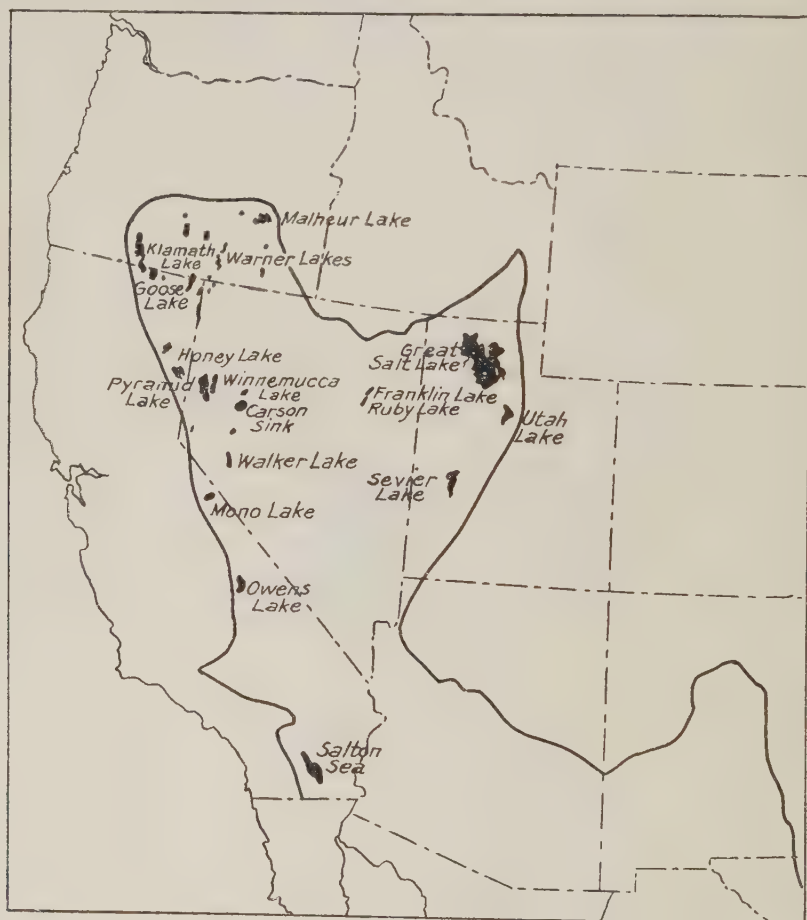


FIG. 2.—Map of the present lakes in the Basin-and-Range Province.
(From Bull. Geol. Soc. of Amer., vol. 33, 1922, by O. E. Meinzer.)

The supposition of various students that the Pleistocene lakes in the Great Basin can be accounted for by a rather slight change of existing conditions is correct, in so far as no great actual increase of humidity is necessary, because the region now has so little precipitation. Relatively, the moist conditions must have been very much greater than at present.

The most striking feature in the Pleistocene of the Great Basin is the incongruity between the vast extension of the lakes and the insignificant glaciation (cf. p. 68). Very noteworthy also is the scantiness of delta formations in Lake Bonneville during the Bonneville stage. Only the American Fork, Rock Creek, Spanish Fork, and probably Hobbie Creek, Spring Creek, and Ogden River formed deltas, most of which were very small (Gilbert, 1890, pp. 160-165). The Ogden River delta was formed in the almost closed bay east of Ogden. Spring Creek is a small brook discharging into Cache Bay. The other creeks belong to the Utah Lake Basin. Rock Creek is a small stream near Provo. No deltas whatever were developed on the western side of Lake Bonneville. During the Provo stage of Lake Bonneville, however, much larger and more numerous deltas were formed.

In Lake Lahontan no well-developed deltas were formed, because the lake was too inconstant in level, and the rivers mostly entered the lake in narrow bays and estuaries (Russell, 1885, p. 123).

These conditions and facts may indicate that, especially during the Bonneville stage, the precipitation was not particularly great; for heavy precipitation should have caused either more extensive glaciation or larger deltas, this latter, if summer precipitation was predominating, or if the summers were warm—which hardly was the case—so that the snow which fell in winter melted during summer. The scantiness or absence of deltas can not be ascribed to very short duration of the Bonneville stage, for the shore-line is remarkably well developed.

The Provo stage of Lake Bonneville, judging from the development of its deltas and shore-line, was of longer duration and was moister and colder than the Bonneville stage. It seems probable that the lake during this period would have risen above the Bonneville strand, had it not found an outlet.

While Lake Bonneville was nourished by streams from the mountains on the east and southeast, Lake Lahontan was largely fed by rivers rising in the Sierra Nevada and by the Humboldt River, draining the northeastern part of the Lahontan area. Lake Mono, as now, received its water-supply from the Sierra, and may have taken its highest stand, during which it filled about one-half of its drainage area, subsequently to the melting of the glaciers descending from the mountain range.

Thus, the time of the expansion of the waters in the Great Basin appears to have been characterized by heavier precipitation than the present time and by little evaporation, due to low summer temperature, which probably is the first factor as well as a consequence of glaciation. A relatively greater part of the precipitation than now may have come in the form of rain, and a relatively larger quantity may have fallen over the lowlands and the lakes.

The relative importance of the increased precipitation and decreased evaporation is difficult to estimate. That the last-mentioned played an important rôle is shown by the large lakes, the relatively insignificant glaciers which speak decidedly against heavy snowfall, the scanty deltas from the Bonneville stage, and the difficulty of conceiving that very much more moisture than now could be brought over the mountains into the basin.

V. AGE OF PLEISTOCENE LAKES IN GREAT BASIN.

Facts bearing directly on the time of the Quaternary lakes of the Great Basin are few. The highest stage of Lake Mono was reached after, probably shortly after, the maximum extension of the glaciers in the adjacent Sierra Nevada (Russell, 1889, p. 369; Gilbert, 1890, p. 314). This is shown by shore-lines on the inner as well as on the outer sides of the moraines left by the glaciers and by deltas formed between the embankments. On the other hand, the Bonneville shore-line was developed before the largest expansion of the Wasatch glaciers, which latter extended below it (Gilbert, 1890, p. 310; Atwood, 1909, pp. 91, 92). The waning of the glaciers began during the Provo epoch. The moraines are not washed at the Bonneville level, but on Little Cottonwood Creek are partly buried beneath deposits of the Provo stage. Lake Bonneville, it should be remembered, in distinction from Lake Mono, did overflow and cut a deep outlet; otherwise it also might have attained its highest level after the retreat of the glaciers from the lowest moraines. The development of the Bonneville shore-line shows that the lake stood at the same level for some time, though perhaps not very long. Gilbert (1890, p. 171) considers an equilibrium between water-supply and evaporation highly improbable, and thinks that the height of the Bonneville shore-line was determined in a certain sense by overflow. That a barrier of alluvial material could regulate so large a lake with varying water-supply seems, however, still more improbable. As soon as the supply increased the outflow must have been enormous, the water-masses irresistible, and the barrier rapidly removed. This idea of Gilbert stands in sharp contrast to his opinion of the catastrophic drainage as described by him (1890, p. 177). The lake-level, therefore, could hardly have reached the brim of the basin at the Red Rock Pass, but the Bonneville stage may really represent an equilibrium between water-supply and evaporation, especially if, as held on page 73, evaporation and temperature played a greater rôle in the extension of the lake than did precipitation. When the lake began to rise it very soon reached the level of the pass and was rapidly drained.

The depauperation of the mollusks of the fresh Lake Bonneville, as Gilbert (1890, pp. 300, 318) points out, most likely is to be ascribed to low temperature.

From these facts, from climatological discussions, etc., Russell (1889, p. 371) and Gilbert (1890, p. 318) conclude that the highest stages of the lakes closely coincided with the epochs of maximum glaciation in the adjacent mountains and in the northeastern part of the continent. This conclusion is strongly supported by the climatic conditions, as the analysis and review given on pages 54 to 66 show. The glaciations were connected with such great changes of climate that it is unthinkable that the Great Basin should not be influenced by them. Low temperature checking evaporation probably made itself felt when the ice-sheet began to grow in Canada. Later also precipitation must have become greater. These cooler and moister conditions, begun at an early stage of the glaciations, gradually increased, and the highest point of moisture was reached during the pluvial periods which seem to have been a consequence of the great climatic change which checked the further expansion of the ice-sheets and caused their disappearance. The

different lakes in the northern part of the Great Basin must have expanded contemporaneously, but, on account of local conditions, the highest levels possibly were reached at somewhat different times. At the height of the glacial epochs the highest mountains were glaciated.

Seen from the other side, the glaciations and the expansions of the lakes in the Great Basin region must have had correlatives in the northern part of the continent, and the glaciations are the only ones in these areas.

In post-glacial time, as the short review of the climatic evolution in some of the best-known regions shows (cf. pp. 63-66), the climatic fluctuations, though in part rather marked, have not been very great. It can be added that they have not been great anywhere where studied. Hence it is practically certain that the climate in the Great Basin during the post-glacial epoch has not been so moist that it could have given rise to such large lakes as Bonneville and Lahontan, for what would have caused such marked climatic change without correspondence in other parts of the earth?

Accordingly, the facts bearing on the age of the lakes, as well as the accumulated knowledge of Pleistocene climatic conditions, seem to show that Gilbert and Russell were right in their opinion that the lakes coincided with the glaciations in the adjacent mountains and the maximum extensions of the ice-sheets in the northern part of the continent and the first parts of the ice retreat. The dating of the lakes, therefore, can be made by help of the knowledge of the time of the glacial epochs. The last Bonneville and Lahontan stages corresponded to the last, the Wisconsin, glaciation and the earlier stages to the earlier glacial epochs.

As yet only three glaciations have been recognized in the Southwest and only two high-water stages in Bonneville and three or perhaps four in Lahontan as explained later, but more detailed studies and better exposures of the sediments would no doubt reveal as many glaciations and moist periods as there were glacial epochs in the North.

The mammal fauna obtained from the deposits of Lake Lahontan has played some rôle in the determination of the time of the last high-water stage of the lakes. In the canyons of the Humboldt and Walker Rivers Russell (1885, p. 238; cf. Osborn, 1910, p. 468) found remains of an elephant (*Elephas colombi*?), a horse, a bison, and a llama, none of which has been identified specifically. Seldom more than one or two bones of the same individual were found at a single locality, but of the elephant a nearly complete skeleton was obtained. From Lahontan shore-gravel in the Astor Pass, 4 miles west of Pyramid Lake, another fauna, obtained by J. C. Jones, has been described by Merriam (1915, 1918). The forms are *Felis atrox* Leidy, camelid near *Camelops*?, *Equus* near *pacificus*, *Equus* near *occidentalis*, undeterminable fish, and undeterminable bird. Merriam (1918, p. 520) finds that the fauna must date from a considerably remote time, and sums up his opinion as follows:

"It seems possible that the Lahontan fauna may be representative of a period including the Fossil Lake and Rancho La Brea stages. On this basis it would appear that, whatever the more exact correlation, the Lahontan stage represents a time when life of this region and that of North America in general was made up of mammal types of which from 60 per cent to 70 per cent have since become extinct and are replaced by new types."

Russell states that all bones, with the exception of a single vertebra found in the medial gravels, were obtained from the upper lacustrine beds, but his

interpretation of the origin of some of the beds appears to be wrong. In the Walker Canyon, where most of the bones were found, he assigns two clay beds with an intervening gravel bed, probably representing two moist periods and one dry period, to the "upper lacustrine clays," and in the Humboldt Canyon, at Rye Patch, where the elephant was found, he seems to assign an underlying alluvial clay bed to the last lacustrine stage. It is, accordingly, not known from which stage the fauna dates, but probably it should be assigned to the last lake period. The fauna from the Lahontan shore gravel at Astor Pass may occur in a secondary position. Thus, the mammal fauna may not have a bearing upon the time of the last expansion of the lakes.

From what has been said it follows that the present writer can not share Jones's (1914, 1925) opinion that Lake Lahontan had nothing to do with Lake Bonneville, but began its existence somewhat more than 2,000 years ago and reached its maximum extent about 1,000 years ago. It must be asked how the climate could be moist in the western part of the Great Basin and at the same time dry in the eastern portion, and what the large Lake Bonneville corresponded to in the Lahontan Basin.

Jones's estimates are essentially based upon the rate of accumulation of chlorine and sodium in the basin by the Truckee River. The ratio between the sodium-potassium and calcium in Pyramid-Winnemucca Lakes and in the Truckee, and the approximate correspondence between the estimated amount of calcareous tufa and the amount of deposited calcium carbonate as calculated from its low percentage in the lakes compared to the river, in Jones's opinion, show that no salts have been lost in post-Lahontan time through overflow or through desiccation and burying beneath playa clays.

The factors in Jones's calculations and estimates, however, are too uncertain to prove his view convincingly. Calculation of the amount of deposited calcium carbonate is not reliable, because of the low percentage of calcium in the lakes and the very great multiplying. Estimation of the existing calcareous tufa is another difficulty. The very estimation of what is left and seen is no easy matter, and it is not known how much tufa has crumbled into pieces—the tufa towers are rapidly decaying (cf. Russell, 1885, pp. 207, 208)—are covered by sediments, or are submerged beneath the waters of the lakes. The water of the Truckee might have changed chemically. Therefore neither the question of age nor that of desiccation appears to be settled by the chemical studies. The low salinity of Pyramid, Winnemucca, and Walker Lakes probably has no bearing upon the age of Lahontan (cf. p. 102). There appears to be nothing indicating that the history of Lake Lahontan fell within the last few thousand years.

Nor can this writer share Keyes's (1917*a*, 1918, 1918*a*) opinion regarding Lake Bonneville, which is opposed to that of Jones regarding Lahontan. Keyes holds that Lake Bonneville was not caused by notably moister climate than that at present, but came into existence by ponding of a throughflowing river by extensive uprising of the Colorado Dome on the southeastern side of the Great Basin. This happened long ago. Even the time of greatest expansion was long prior to the commencement of the glacial period. According to Keyes the Red Rock Pass, at the northeastern corner, which Gilbert regarded as the outlet, was instead the main inlet, the channel of the big stream which fed the lake. When this stream was diverted through lava-

flows, so as to give rise to the present Snake River, the end of the history of Lake Bonneville had begun.

Disagreeing with Keyes on many points, I will confine myself to two fundamental questions. Keyes (1917*a*, pp. 360, 363, 365) discusses the necessary warping for turning the present Snake River into the Great Salt Lake Basin through the Red Rock Pass, a warping of more than 275 feet; but since it is the greater Bonneville which he intends to explain, he evidently should have discussed the inflow of the ancient Snake River at the level of the Bonneville shore-line, which at present lies more than 645 feet above the river.¹ A warping of 645 feet, however, is out of all question; for the tilting of the Bonneville shore-line, in the northeastern part of the ancient lake, is less than 100 feet in 30 miles (Gilbert, 1890, pl. 46, p. 368), and the distance from the Red Rock Pass to the Snake River is only 55 miles. Furthermore, there is no delta deposited by the supposed master stream, a very serious lack (see Gilbert, 1890, pp. 162, 163). Therefore, it is evident that the Red Rock Pass at no time since long prior to the highest stage of Lake Bonneville has been an inlet, but must have been the outlet of the lake, as held by Gilbert.

Thus, it seems that Bonneville, Lahontan, Mono, and other waters in the Great Basin were due to the combined effect of decreased evaporation because of low summer temperature and relatively heavy precipitation connected with the climatic changes that ended the expansion of the ice-sheets and made these disappear. The pluvial periods coincided with the maximum extension of the land ice and the early stages of ice retreat. A pluvial period and an expansion of the lakes represented each glacial epoch; the last high-water stage corresponded to the last, the Wisconsin, glaciation, and to the last glaciation in the mountains in the West. The last Bonneville, Lahontan, and Mono, consequently, date back about 30,000 to 35,000 years.

¹ The elevation of Pocatello, lying somewhat above Snake River is 4,460 feet (Lee, 1916, p. 123), and that of the Red Rock Pass is about 4,735 feet. This pass lies about 370 feet below the Bonneville shore-line, which Gilbert (1890, p. 174, plate 28) traced continuously almost to the very pass. The shore-line here lies at an elevation of 5,105 feet, or 906 feet above Great Salt Lake (Gilbert, 1890, p. 365), the zero of which has an elevation of 4,199 feet (Lee, 1916, p. 95, plate 15).

VI. PLEISTOCENE CLASTIC DEPOSITS IN GREAT BASIN.

THE LAHONTAN BASIN.

The clastic deposits in the Lahontan Basin are well exposed in the canyons of the Humboldt, Truckee, Walker, and Carson Rivers, of which the three first mentioned were visited by the writer. The reader who compares the following descriptions of profiles with those given by Russell in his monograph will sometimes find great and inexplicable differences. Regarding this fact it may suffice to say that, with full knowledge of Russell's statements, the writer made his field-notes and sketches strictly in accordance with observed facts and conditions. The different interpretations of many deposits is ascribable to the developed knowledge of the sedimentary processes which we now possess.

THE HUMBOLDT CANYON.

From its entrance into the area of the ancient Lake Lahontan at Golconda the Humboldt River flows in a channel excavated in Pleistocene sediments. In the upper part of its course in the ancient lake down to Mill City and in its lower course from below Woolsey, the river essentially is a surface stream with low banks here and there. At Mill City the river channel begins to deepen. It increases gradually in depth till at Rye Patch this reaches over 200 feet. Then the canyon grows shallower to below Woolsey. The sediments, consequently, form a broad barrier with very gentle side-slopes across the valley. In this canyon, between Mill City and Woolsey, the Pleistocene sediments at many places are excellently exposed.

PROFILES AT MILL CITY.

Profile 1, figure 4, was measured at the sharp bend of the Humboldt, a few hundred yards north of the railroad station; profile 2, about 200 yards west of No. 1; and No. 3 at an old dam 300 yards north of the bridge across the

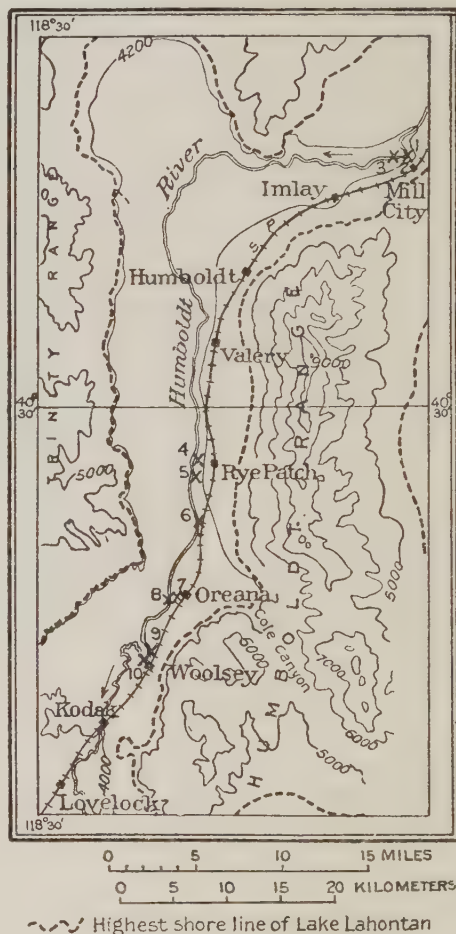


FIG. 3.—Map showing position of sections examined in Humboldt Canyon, Nevada.

river, about a mile northwest of Mill City. All three profiles show two beds of gray lacustrine clay, separated by layers of sand and gravel. These latter have different origins, but all indicate a low-water stage. In profile 1, layer 2 consists of fine gray-white sand and silt in very irregular stratification, and evidently is of eolian origin. In profile 2, layer 2 is of the same character and origin, while the underlying layer 3 may be a shallow-water or subaerial deposit. In profile 3, layers 3 and 5 may be bajada deposits, and layer 4 a playa deposit. Layer 5 rests on a somewhat eroded clay surface. It is faintly rusty, and layer 3 strongly so.

Just to the side of profile 1 the strata rise toward the east, showing underneath layer 5 a bed of coarse gravel with cobbles up to 5 inches in diameter. This gravel-bed is more than 12 feet thick. Together with layer 5, a mixture of gravel, sand, silt, and clay, gray, rusty, and pink in color, it forms an alluvial deposit. Layer 4 consists of comparatively pure gravel and probably is a shore deposit.

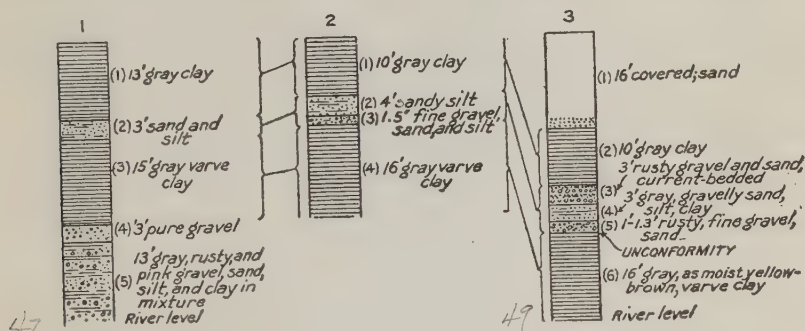


FIG. 4.—Profiles at Mill City.¹

The clays are yellow-brown and appear homogeneous, when moist, but in dry condition they show lamination by alternation of layers of almost white silt or silty clay and of gray-brown fine clay. The clay laminae are sharply limited downward as well as upward. The clays in dry condition resemble rather closely the late-glacial clays in the Hudson Valley, which when dry also are light-gray, and show only faint lamination. The lamination no doubt is seasonal. Similar clays were observed farther south in the Humboldt Valley and at Salt Lake City and Leamington in Lake Bonneville (cf. pp. 81, 83, 94, 96), but not in the western part of Lake Lahontan or in the Mono Basin. Since these latter basins at the foot of the Sierra Nevada, more directly than the eastern part of Lahontan, were fed by streams coming from melting glaciers, the clays may or may not be of glacial origin or correspond to the late-glacial clays in the glaciated regions. There are known to be different kinds of seasonally banded clays, but very little is known about the physical conditions of their formation.

In the clay at Mill City the lamination is not so distinct that sure measurements can be made, but clear enough to give a good idea of the rate of sedimentation. At locality 1, 40 annual layers or varves were found in 3.3 feet of clay; the varves accordingly average an inch in thickness. A few hundred yards south of this locality the average thickness of 35 measured varves was

¹ The term "unconformity" in the figures should be "disconformity."

1.5 inches. This shows that the deposition of the clay-beds took a very short time, that of the lower bed at locality 1 less than 200 years.

Profiles similar to those at Mill City were observed on the north side of the river, 2 to 3 miles west of Mill City. At one place the gravel-bed was missing, but the disconformity was recorded by an erosion surface.

To sum up: The exposed sediments at Mill City record two high-water stages during either of which the water-level reached or almost reached the Lahontan shore-line.

PROFILES AT RYE PATCH.

Profiles 4, 5, and 6 are from the highest part of the barrier of Pleistocene sediments cut through by the Humboldt. They are from the eastern side of

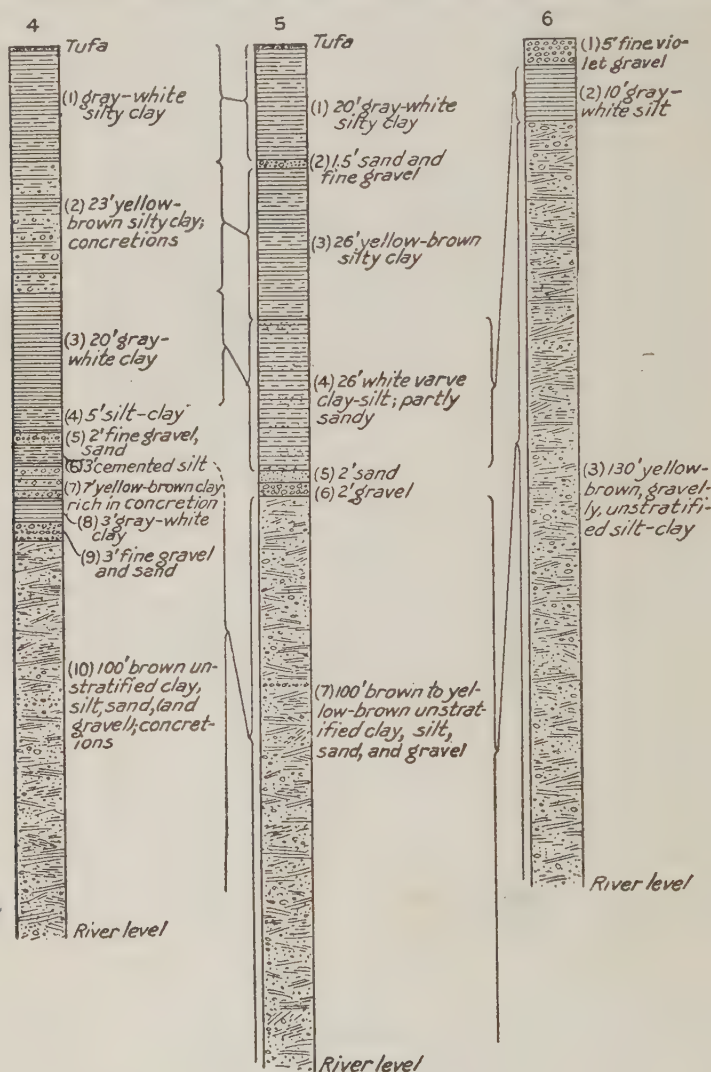
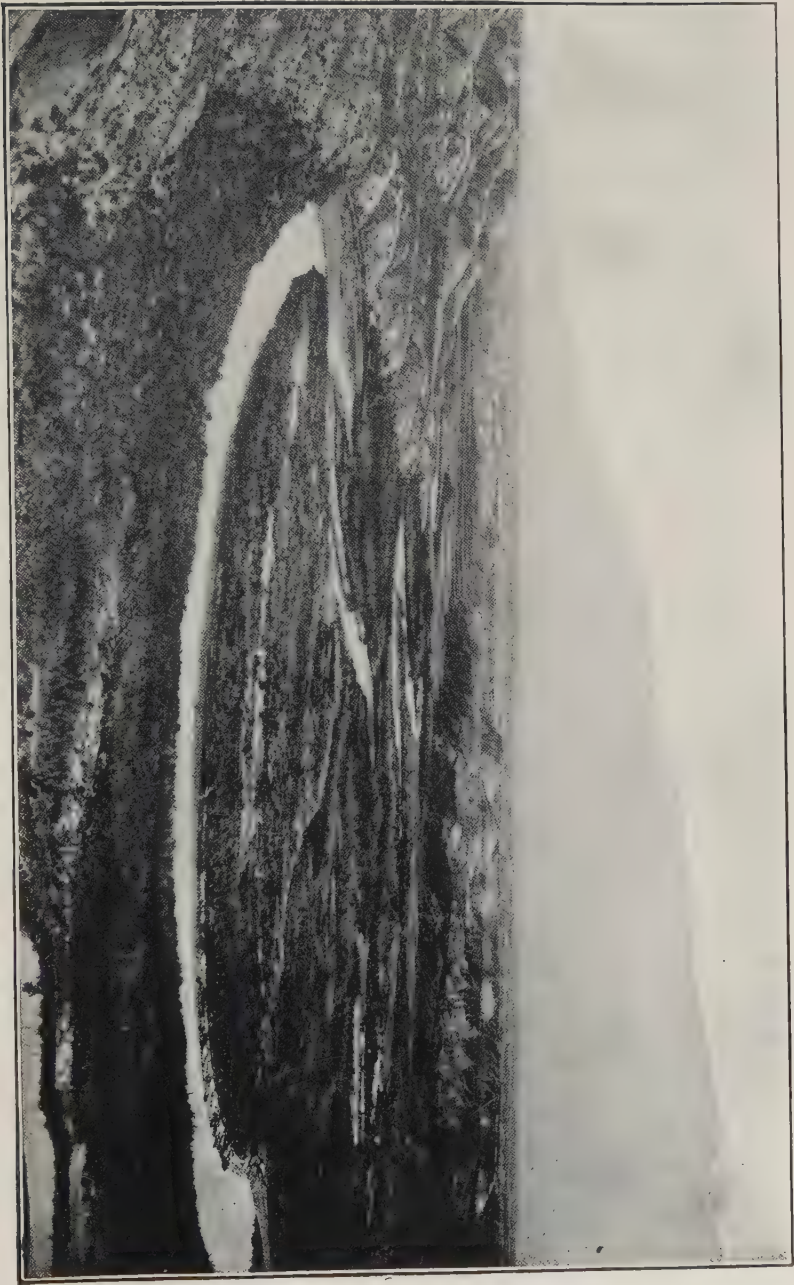
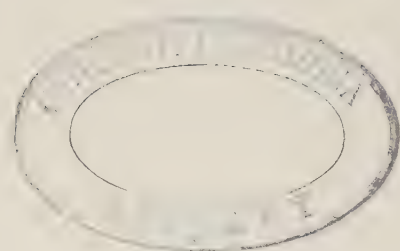


FIG. 5.—Profiles at Rye Patch (4-6).



View of the Humboldt Canyon near Rye Patch, Nevada. (U. S. Geol. Survey.)



the wide canyon. Profile 4 was measured opposite Rye Patch, profile 5 a mile south of No. 4, and profile 6 at 4 miles south of No. 4.

Owing to different coloring, the beds stand out very distinctly from a distance and can be followed by the eye for miles. The strata rise southward, so that at profile 6 there is only one thin bed of lacustrine clay, corresponding to the lower clay bed in profiles 4 and 5. Southward from profile 6 and as far as the eye can reach the profile does not change, but a bed of white clay silt overlies the yellow-brown gravelly clay.

The lower yellow-brown bed in each profile is the same. At profile 5 it consists of clay silt, which in some strata, particularly in the lower two-thirds of the exposure, is sandy or gravelly. Very few pebbles are as large as eggs. In the upper third the clay-silt is quite pure. Northward the material gradually becomes finer, and gravel forms only an inconsiderable part. The deposit is usually cemented, particularly in the upper part. Concretions are common all through the bed. The whole bed lacks distinct stratification. The origin of the deposit is obvious. The coarsest material and highest portion of the deposit occur some miles south of Rye Patch, where the valley is narrowest. The material was washed down from the bordering mountains by the waters of occasional showers. The fans which were built out from the mountain sides met in the center of the valley and formed the transverse barrier.

Layers 8 and 9 in profile 4 lack similar correlatives in the other profiles. They seem to represent lake deposits and may have been laid down in a perennial lake ponded north of the barrier. This could have been a local affair of short duration caused by a little swing toward moister conditions. Layer 7 in the same profile, again, is of subaerial origin. It resembles layer 10 and is rich in concretions. The origin of the overlying silt, layer 6, is not quite clear. Layers 4 and 5 in this profile and layers 5 and 6 in profile 5 are probably shore and shallow-water deposits.

The gray-white clays are lacustrine. At locality 4 they are fine-grained and homogeneous. At profile 5 the lower clay-bed shows a rather distinct lamination. The 7 lowest feet are sandy, constituting seven annual layers. The following 5 feet, which consist of fine clay, show 23 varves. The number of varves in the upper silty part of the clay bed could not be learned, but it surely is not large.

The yellow-brown clay beds, layer 2 in profile 4 and layer 3 in profile 5, as well as the violet gravel-bed at the top of profile 6, may be of subaerial origin as indicated by consistency, color, and abundance of concretions. In moist condition the clay is olive-brown.

In all, the exposed sediments at Rye Patch seem to record two stages during which the water-level stood very high, for the surfaces of the lake sediments lie only about 125 feet below the Lahontan shore-line. Besides, they record a preceding lake stage, probably of short duration. Before and between the lake periods no permanent water sheets existed in this part of the valley. After the recession of the last lake, erosion occurred by which the upper beds at profile 6 have been removed and the wide canyon excavated.

On the western side of the rather wide canyon the corresponding beds lie deeper and are thicker. About 3.5 miles south of Rye Patch the alluvial barrier rises rather abruptly from below the river-level almost to the surface and the overlying strata are evenly cut off by recent erosion.

PROFILES AT OREANA.

Profile 7 was measured in a gully between the railroad and the river, 0.5 mile southwest of Oreana, and profile 8 in the bluff on the west side of the Humboldt 0.75 mile southwest of Oreana.

The connection between the beds, as shown in figure 6, is evident in the field, because of the color of the sediments. The light-clay beds are lacustrine and the upper gravel-bed in each profile is probably alluvial. Layer 6, profile 8, shows typical delta structure. Layers 5, 7, and 9 may be lake deposits. The remaining gravel and sand layers may be lake or river deposits. Thus, the exposed sediments at Oreana register two high lake stages and probably an earlier lake state, insignificant in duration and extension.

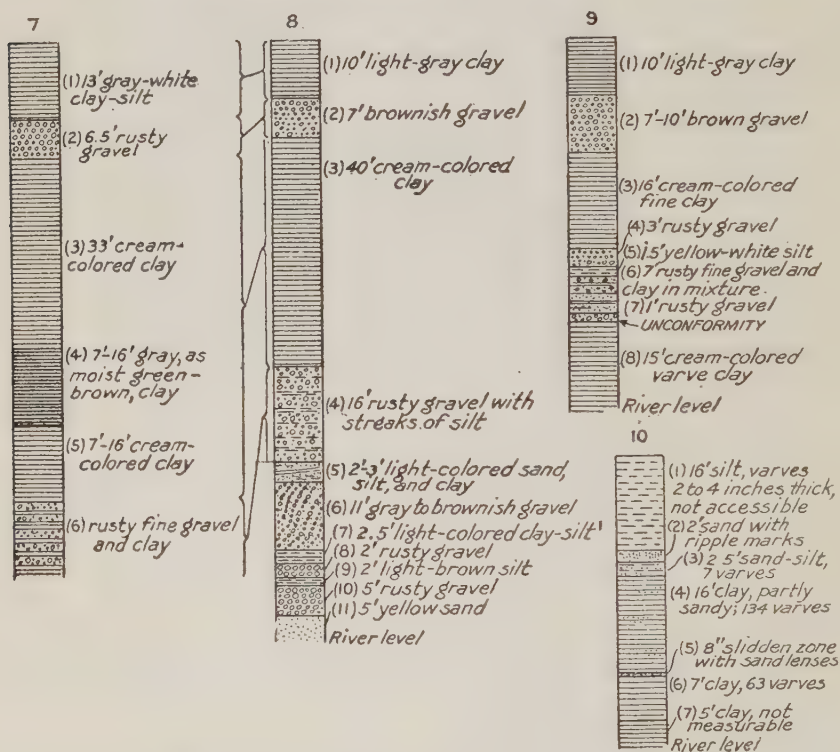


FIG. 6.—Profiles at Oreana and Woolsey (7-10).

PROFILES AT WOOLSEY.

Profile 9 was measured in the bluff on the west side of the river, 0.75 mile northwest of Woolsey. The lower clay bed is distinctly laminated, but, since it was not accessible, no measurement was made. The intermediate clay shows less distinct lamination, while the topmost clay was too greatly covered and weathered to show any lamination. These three thick clay beds evidently indicate three lake stages. The silty layer 5 probably is a lake deposit marking a moister period, but it might be a playa deposit. The consistency

and rusty color of the gravel layers indicate subaerial origin during times of low water. The lowest clay bed is eroded at the top.

At the sharp river bend just west of Woolsey, the high bluff consists exclusively of clay, silt, and fine sand (profile 10). The correlation to profile 9 could not be made out in the field with certainty, but the whole profile probably corresponds to the lowest clay bed in profile 9. In dry condition the clay shows distinct lamination, particularly from some distance. In the moist clay at the river-level the laminæ are too obscure to be measured. The lamination evidently is seasonal (cf. p. 79). Because of the perfectly dry condition of the clay, exact measurement was not possible, but the numbers of varves given in the profile (fig. 6) are practically correct.

SUMMARY.

Summing up the preceding description of the deposits in the Humboldt Valley we find that profile 9 at Woolsey records three distinct lacustrine periods; profiles 4 at Rye Patch and 8 at Oreana record two high-water stages and one preceding low lake stage of short duration; and the other profiles, except No. 6, which is eroded at the top, record two extensive floodings of the valley. Before and between the lake stages the valley was a desert, as to-day. During two of the high-water stages the water-level reached, or almost reached, the Lahontan shore-line, and during at least two of the arid periods the water receded to about the present stand, as indicated by gravels at and near the river-level in profile 8. Since only the upper part of the deposits in the valley are exposed, and since evidently considerable erosion took place each time the water-level was lowered, the records can not be expected to be complete. Correlation between the different groups of profiles must therefore be made with the greatest caution. Profiles 4 and 8, which were measured 8 miles apart on each side of the highest part of the barrier, correspond so closely that it seems likely that they record the same stages. The earliest lake period which they register may have been neither extensive nor long, and probably is not to be correlated with that during which the lowest clay-bed in profile 9 and the entire profile 10 were deposited. Hence the sediments in the Humboldt Canyon appear to record three stages during which the valley was occupied by deep lakes and one ancient stage during which the lower parts of the valley were permanently flooded. When the lake fell for the last time a separate lake fed by the Humboldt must have become ponded north of the barrier until it was cut through.

THE TRUCKEE CANYON.

From its entrance into the area of the ancient Lake Lahontan to its terminus in Pyramid Lake the Truckee River flows through a canyon in Pleistocene sediments. Good, high sections are to be found here and there along the whole of this course, but the best exposures occur at Numana, 6 miles south-east of Pyramid Lake, and just north of the narrowest part of the valley, the Narrows, where the river has cut a gorge in rock.

PROFILES AT NUMANA, NORTH OF THE NARROWS.

Profiles 11, 12, 13, 14, and 15 were measured in the river bluffs at Numana. Figure 7 shows their location. Because of different color and consistency, the thick beds can easily be followed by the eye, so that the correlation indi-

cated in figure 8 is certain. The thin layers are very inconsistent, and consequently can not be correlated. On the whole, the profile changes rapidly. The two upper clay-silt beds and the tufa layers in profiles 12, 13, and 14 evidently mark two lake stages. With which of these the clay-bed in the incomplete profile 11 is to correlate is not clear. Bed 4, profile 12, contains a layer of white marl, 4 inches thick. The intervening gravel-bed is of medium coarseness and is violet and rusty in color. Here and there it contains streaks of sand and sandy silt. At places it shows distinct current bedding. It seems to represent an old river-bed.

The gravel underneath the lower clay-bed, in profiles 12, 13, and 14, corresponds to the upper part of bed 4 in profile 11. At 11 it consists of relatively fine gravel, but as one approaches the hill at the Narrows it becomes

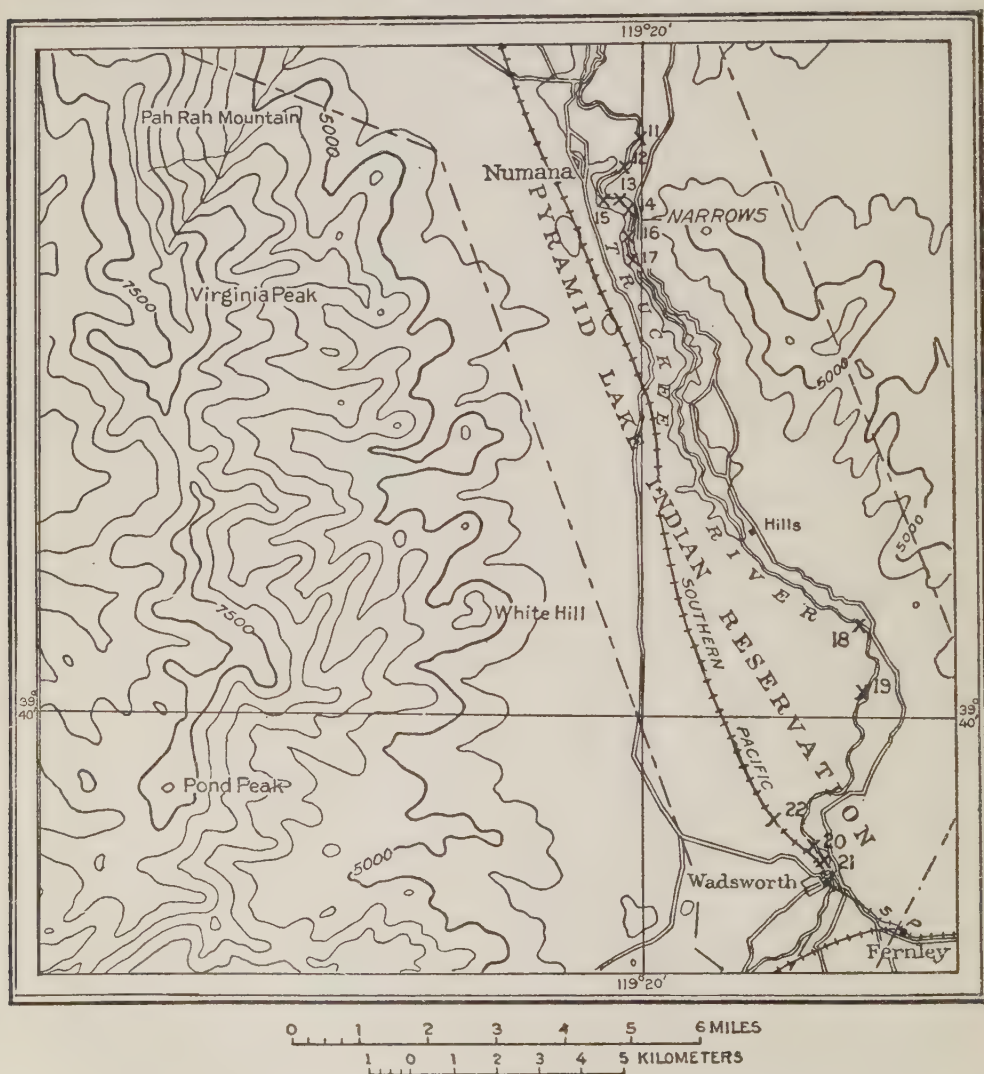


FIG. 7.—Map showing position of sections examined in the Truckee Canyon, Nevada.

very coarse, containing many boulders more than 2 feet in diameter. In profile 14 it rests on an eroded surface. The big boulders may have been washed down from the neighboring hills during cloudbursts. The bed consists of pure gravel, so that it must have been assorted by water.

Below the coarse gravel in profiles 12, 13, and 14 there are alternating layers of clay, silt, sand, and gravel. They are mostly thin and little persistent, rapidly wedging out. They might essentially be of lacustrine origin and indicate oscillations of the lake-level, but they could perhaps, at least partly, be fluvatile. In the middle of the gravel-bed, in profile 11, is a 2-foot outfading layer of white marl, and in the lower part a 6-foot outwedging bed of light, well-stratified, somewhat sandy clay-silt.

On the south side of the river, in an irrigation ditch in the bottom of the canyon, the section shown in profile 15 was observed. The clay-silt apparently is lacustrine. Its top is considerably eroded. The gravel is very coarse; many boulders measure 2 feet in diameter. Regarding the relationship to the other profiles, only enough could be made out to indicate that this profile represents a lower horizon.

The sediments at Numana, consequently, seem to record four lake stages, of which the second in order probably was not extensive (cf. p. 83). During the first dry stage, recorded by the gravel in profile 15, the water-level must have receded about to the present stand, and during the other arid periods almost as far.

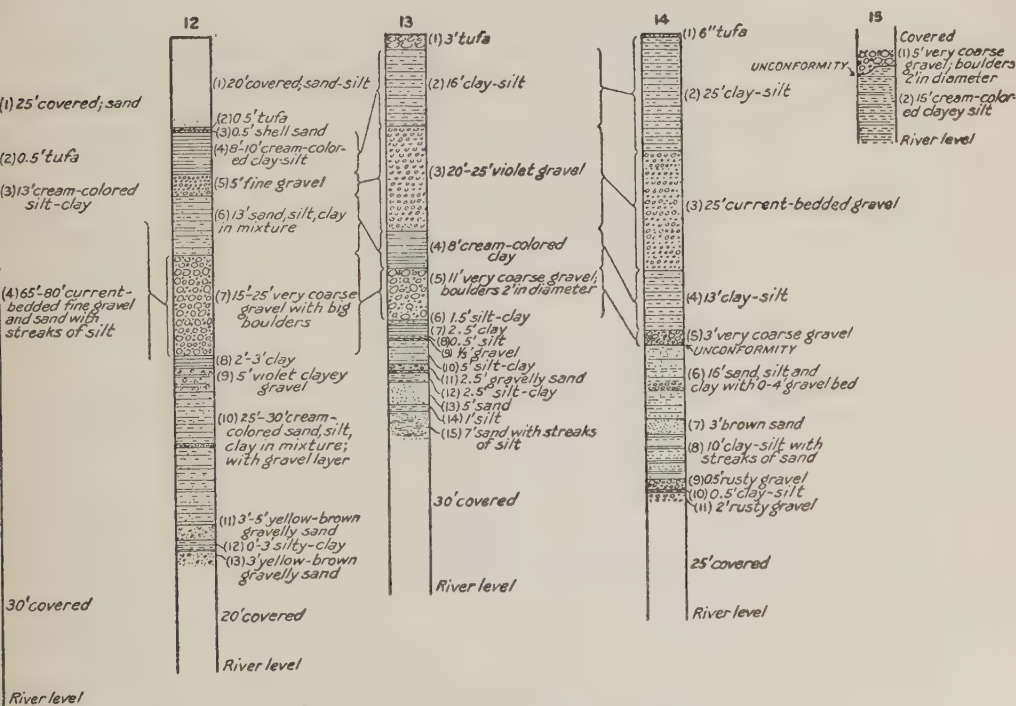


FIG. 8.—Profiles at Numana, north of the Narrows (11-15).

PROFILES AT NUMANA, SOUTH OF THE NARROWS.

Profiles 16 and 17 were measured on the west side of the canyon south of the gorge, 1 and 1.33 miles respectively south-southeast of Numana station. In profile 16 the beds 2, 3, 4, 8, and 10 evidently were deposited in deep water and layers 5 and 7 in shallow water, at the shore or perhaps in a river. The lowest gravel, bed 11, contains big boulders, is red-violet in color, and likely of sub-aerial origin. It perhaps rests on rock, which crops out in the canyon a few hundred yards north of the profile; but this could not be made out with

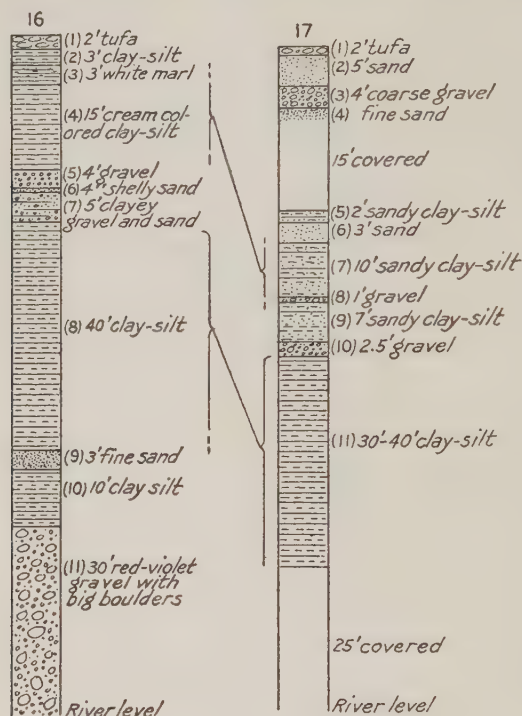


FIG. 9.—Profiles at Numana, south of the Narrows (16, 17).

certainty. The strata dip southward, and at profile 17 the bottom gravel has dived below the bottom of the canyon, showing that the water-level stood lower than at present. The clay-beds 7 and 11, in profile 17, are the same as beds 4 and 8 in profile 16, but for the rest the correlation could not be determined with certainty in the field. It is probable, however, that layers 8, 9, and 10 in profile 17 correspond to layers 5, 6, and 7 in profile 16. Layer 8 in profile 17 certainly is only a foot thick, but it contains cobbles as large as a fist, and, since it rests between two clay-beds, must mark a decided fall of the water-level. This bed, as well as other beds, might have been considerably thicker. Profile 17 therefore probably records three lake stages.

The relationship between the beds north and south of the gorge could not be made out in the field, because the beds rise over the rock sill, and the bluffs are covered by debris. Connection between the profiles by comparison can not

be made with certainty, for it is not known how completely they record the events nor what events the basin has passed through in Pleistocene time; but it is likely that the greater parts of the profiles correspond.

PROFILES AT WADSWORTH.

Profile 18 is from the west side of the Truckee, 4 miles north of Wadsworth. The lower sand, layer 7, is violet in color, but it would perhaps be rash for that reason to assume it to be of subaerial origin. The clayey gravel, bed 5, which also is violet, rests on an eroded clay surface, as figure 11 illustrates, and in all likelihood is alluvial. The upper sand, layer 3, may mark a slight oscillation of the lake-level. The profile, consequently, represents two or three lake-stages and one or two arid periods.

Profile 19 was measured in the west river bluff about 2.75 miles north of Wadsworth. The gravel-bed, which varies in thickness from 2 to 5 feet and contains stones large as a fist, evidently marks a dry period between two moist

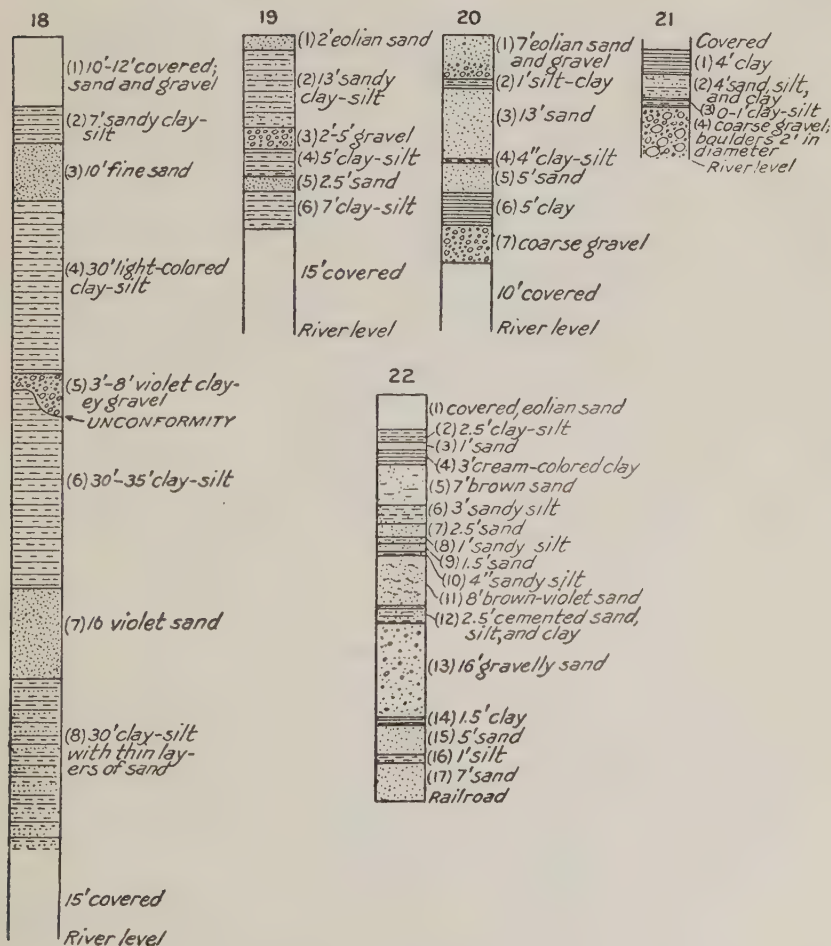


FIG. 10.—Profiles at Wadsworth (18-22).

stages represented by the clays. The sand-bed, layer 5, probably marks only a slight fluctuation of the lake-level.

Profile 20 is from the river, 0.33 mile north of Wadsworth. The lower gravel-bed, bed 7, the base of which was not observed, contains big boulders. The clay, layer 6, shows lamination due to very thin laminæ of fine sand. The beds 2 to 5 may indicate changes in the lake-level or in the strength of the current of the river.

Profile 21 was measured on the river at the northern edge of the village. The gravel-bed, which probably is the same as that in profile 20, here contains

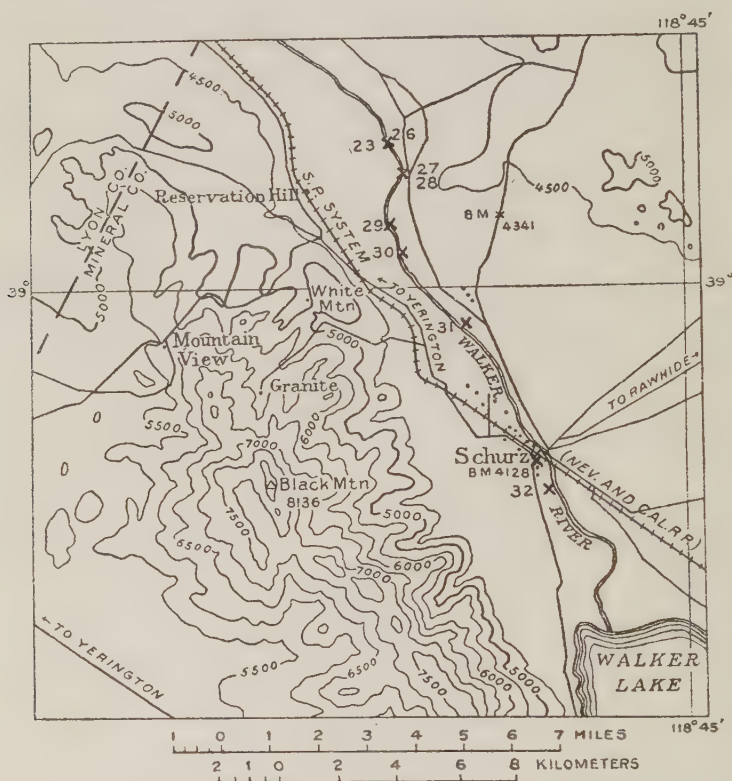


FIG. 11.—Map showing position of sections examined in Walker Canyon, Nevada.

boulders up to 2.5 feet in diameter. The nearest hill being 2 miles distant and the grade insignificant, the boulders can only have been brought here by the enormous transporting power of a desert stream during cloudbursts (cf. Pack, 1923, p. 356). Layer 3 wedges out, probably indicating that it is an erosional remnant. The mixture of fine and gravelly material in layer 2 suggests alluvial origin. The upper clay is lacustrine.

Profile 22 was measured in a railroad cut about 400 yards long, a mile north of Wadsworth. The whole series, which probably overlies profile 20, may be of lacustrine origin. The rapid alternation of clayey, silty, and sandy layers suggests several oscillations of the lake-level.

North of Wadsworth 1.5 and 2 miles there are other railroad cuts 30 and 25 feet deep, respectively, showing clayey silt and fine sand in alternating beds. Between Wadsworth and Fernley there is a sand-pit, showing 50 to 60 feet of pure brown sand.

SUMMARY.

The sediments exposed in the Truckee Canyon record three or perhaps four stages during which the valley lay under deep waters and lesser expansions of the lakes. During the intervening dry periods the lake-levels withdrew to unknown levels, but in at least one period to below the present water-level.

THE WALKER CANYON.

In the upper part of its course over the area of the ancient Lake Lahontan the Walker River is a surface stream. About 20 miles above Walker Lake it begins to excavate a channel in the Pleistocene deposits which here and there are displayed in bluffs some 50 feet high. The sediments consist of alternating beds of clay, silt, sand, and fine gravel. The best exposures are to be found just above, at, and below the sharp river bend opposite Reservation Hill, that is, 6 to 8 miles above Schurz or 10 to 12 miles above Walker Lake.

PROFILES AT RESERVATION HILL.

Profile 23 was measured in the bluff on the west side of the river, 0.66 mile above the bend opposite Reservation Hill; profile 24, 200 yards southeast of profile 23; and profiles 25 and 26, 250 yards east of No. 24.

The correlation of the beds in profiles 24, 25, and 26 became quite clear in the field, and is shown in figure 12. The relationship of these profiles to profile 23 was somewhat difficult to ascertain, but the rusty, sandy, and gravelly beds almost surely correspond to each other. If this is the case, beds 1 to 8 in profile 23 probably correspond to bed 2 in profile 25 and bed 1 in profile 26, and bed 12 in profile 23 to bed 2 in profile 24 and bed 3 in profile 26, etc. Beds 1 to 8 in profile 23 mark only small changes in the level during one and the same lake-stage. Beds 12 and 14 in profile 23 and their correlatives in the other profiles record two earlier moist periods. Gravel bed 13 in profile 23 and its probable correlative 3 in profile 24 is light-gray in color. It is clayey and contains layers of sand and silt. It probably is of alluvial origin. The rusty sand and gravel beds may be shore or river deposits. The top gravel, locality 25, may be alluvial.

In all, the sediments record three stages, during which the valley was flooded by more or less deep lakes, and four dry periods.

Profiles 27 and 28 were measured 100 yards apart in the bluff east of the river, just at its sharp bend.

The correlation between the beds, as shown in figure 12, is certain. The lowest bed from the river-level consists of gravel, sand, silt, and clay, more or less in mixture. It shows good stratification, which is generally caused by streaks of coarse gravel and cobbles 2 to 4 inches in diameter. It contains scattered boulders up to 2 feet in diameter. The coarser material is rather angular, only a little worn. On the whole, however, the material is rather fine, and in great part consists of sand, silt, and clay. It is cemented, so that at many places it forms perpendicular bluffs 50 to 60 feet high. The color is distinctly pink, well distinguished from the rusty color of many other

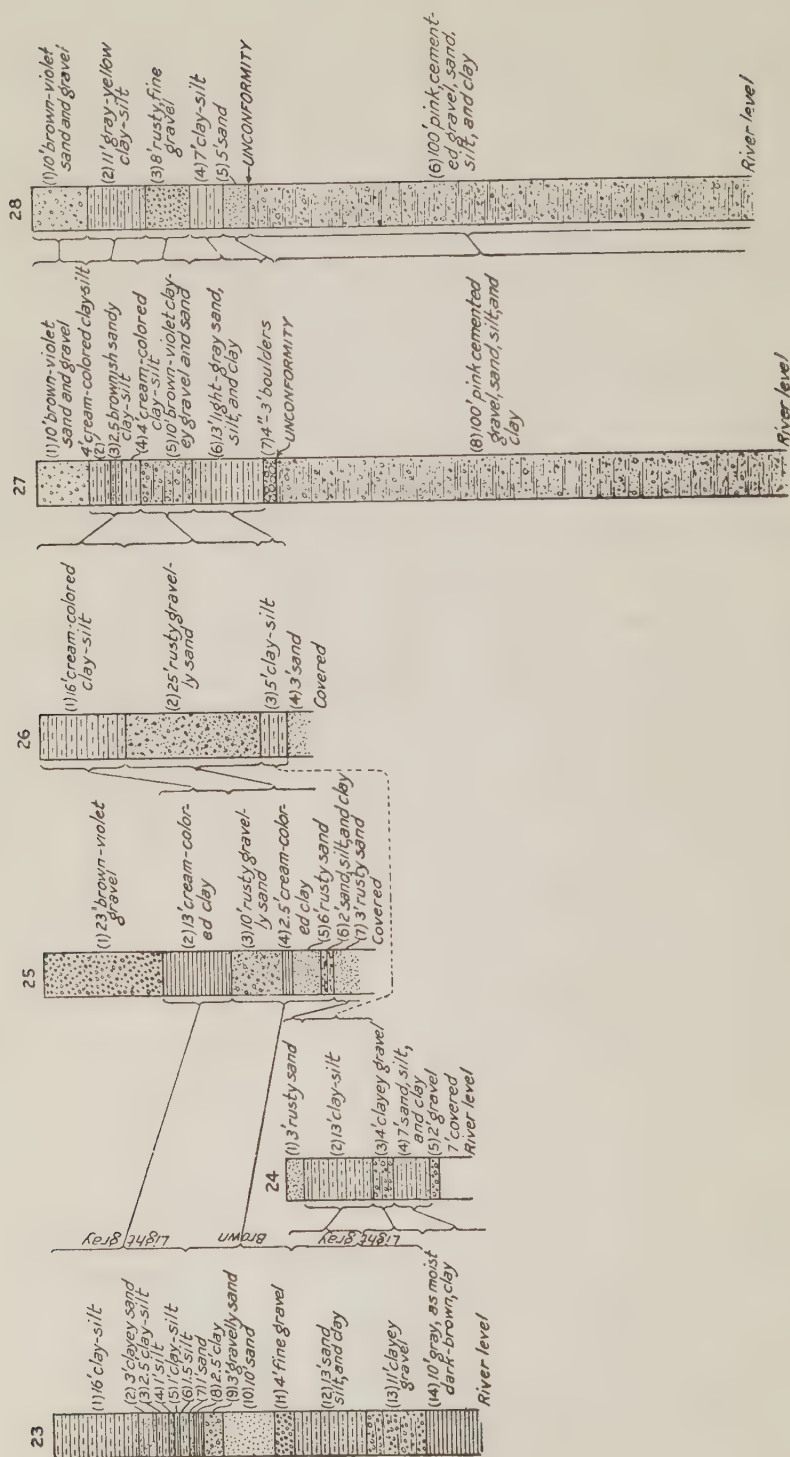


FIG. 12.—Profiles at Reservation Hill (23-30).

beds. The bed increases in height southward and forms a barrier across the valley and is of alluvial origin. As best observed when overlooking the eroded sediments west of the river, from the high bluff on the river, the pink bed underlies all lake sediments that are exposed in the vicinity. The surface of the alluvial bed is very uneven because of erosion.

At locality 27 the eroded alluvial bed is overlain by a cobble bed 4 inches to 3 feet in thickness. At locality 28 this layer is represented by a sand layer. The other beds in the profiles agree, except that the material is somewhat coarser at 27 than at 28.

The beds in profiles 27 and 28, as the conditions in the field show, almost surely correspond to those in profile 26, etc., whose lower strata, however, are more complete. The beds at the river bend lie at a higher level, so that the correlatives of the lower beds in profiles 23 and 24 may have been eroded away or perhaps may not have been deposited. The profiles evidently record two high-water stages and three dry periods.

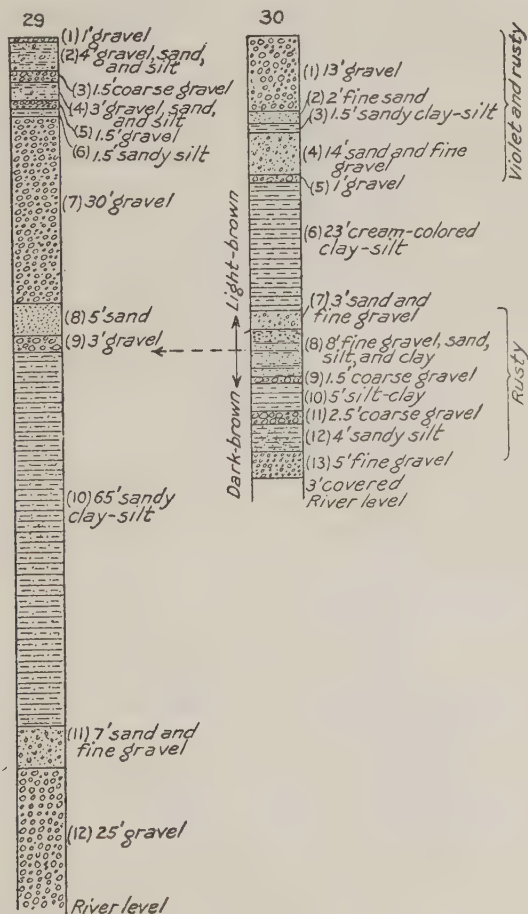


FIG. 13.—Profiles at Reservation Hill (23-30).

Profile 29 was measured 1 to 1.5 miles below the river bend, east of the river, in a depression in the southern part of the barrier. The lower dark-brown strata probably form part of the barrier. The upper light-brown beds may be shore, shallow-water, or alluvial deposits.

Profile 30 was measured 0.66 mile below the narrow part of the canyon, east of the river. The beds below the thick clay-bed are rust-colored. They consist largely of gravel, which partly is rather coarse. Layer 11 contains cobblestones up to 5 inches in diameter. The whole series, including the clayey silt layer, most probably is of subaerial origin. The cream-colored clay-silt bed, layer 6, no doubt is a lake deposit, while the violet and rusty top beds probably are alluvial.

PROFILES AT SCHURZ.

Profile 31 was measured 2.5 to 3 miles above Schurz, on the east side of the river canyon. Most of the beds seem to be shallow-water, shore, or perhaps river deposits.

Profile 32 was measured 0.75 mile below Schurz, in a bluff west of the river. The bottom bed and layers 6 and 4 consist of a mixture of fine gravel, sand,

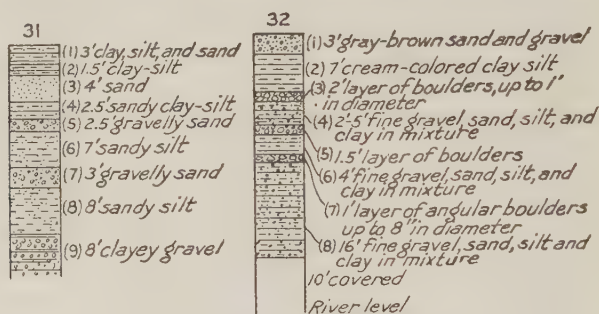


FIG. 14.—Profiles at Schurz (31-32).

silt, and clay, and perhaps are of subaerial origin. The intervening cobblestone layers 7, 5, and 3, of which 7 contains angular boulders up to 8 inches and 3 has boulders a foot in diameter, may indicate only single cloudbursts. If, however, beds 8, 6, and 4 are lacustrine, the cobblestone layers mark dry periods during which the lake receded below the respective levels. Bed 2 evidently is lacustrine, marking a moist period.

THE BARRIER.

The river cut in the barrier opposite Reservation Hill is about 2 miles long. The barrier, as just described, is pink-colored and consists of a mixture of fine and coarse material in which clay and silt predominate. From some 90 feet in height above the river at the river bend, it gradually rises to about 150 feet 1 to 1.5 miles farther down. It here, according to J. C. Jones, reaches to within 10 feet of the Lahontan shore-line and forms the earth surface. Near the highest part the strata dip about 10° northward, but a little to the north they are practically horizontal. The southward slope of the barrier is much steeper. The barrier is of exactly the same nature as the barrier described from the Humboldt Valley (p. 81) and is in reality two alluvial fans which descended from the opposite mountain sides and grew until they met in the

center of the valley. The formation of barriers like these evidently requires a very considerable length of time. The two barriers may be of the same age. They are perhaps preglacial. The barrier gravel at Reservation Hill practically certainly rests directly on rock, which crops out at the river just west of the bend near locality 27. There is here a fault-line running somewhat east of north, and rock is seen on its eastern side.

The deposits below the barrier may show that this was cut through during the different Lahontan stages and that Walker Basin formed part of Lahontan.

SUMMARY.

The deposits exposed in the Walker Canyon record three stages during which the valley stood under water and four arid periods during which the water may have receded to about the present level.

THE BONNEVILLE BASIN.

Exposures of the Pleistocene sediments in the Bonneville Basin, says Gilbert (1890, p. 189), are exceedingly rare, and the base of the beds is seen

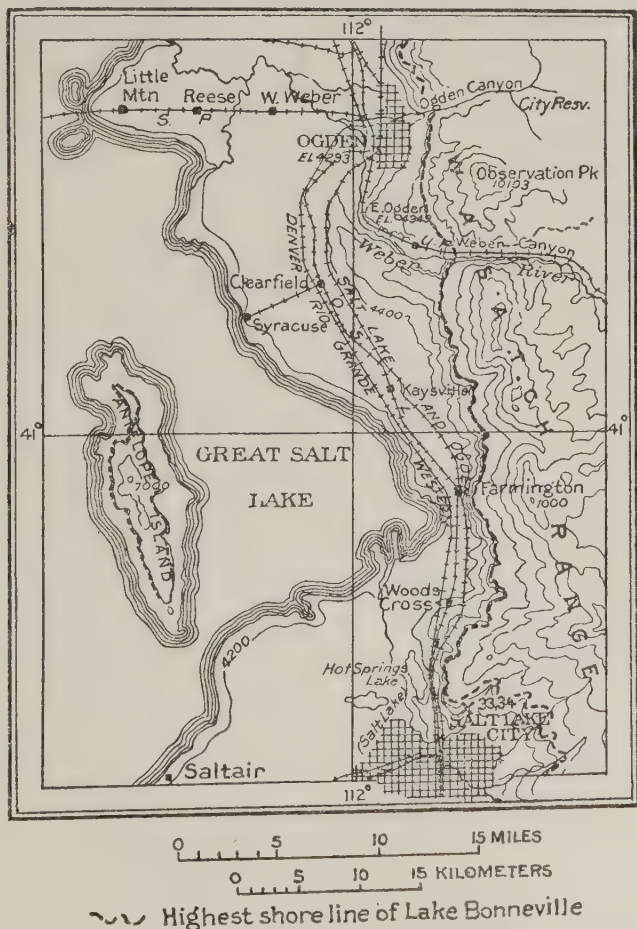


FIG. 15.—Map showing position of sections examined north of Salt Lake City, Utah.

only at their outer limits. This writer had opportunity to study the sediments in the canyon of the Sevier River at Leamington, 85 miles south-south-west of Salt Lake City, and on the eastern border of the basin, between Provo and Ogden. Here the sediments consist of clay, silt, sand, and gravel. White marl was observed only at profile 34 on the City Creek, Salt Lake City, in spite of Gilbert's (1890, p. 191) statement that it affords abundant opportunity for observation.

PROFILES BETWEEN OGDEN AND PROVO.

On the Weber River, just west of Ogden, was observed a fine-grained yellow to yellow-gray almost homogeneous clay. At Kaysville, about half-way between Ogden and Salt Lake City, and at some places about 10 to 12 miles north of Salt Lake City, similar clays were earlier used for brickmaking. West of Salt Lake City, about half-way between the city and Saltair, in ditches about 5 feet deep, a clay which was gray-green in color, homogeneous, greasy, and at some places sandy, was observed. Southeast of Salt Lake City, at Thirty-second street and Highland Drive, a light gray-brown clay with indistinct lamination was used for brick manufacturing. The pits were about 10 feet deep. 11 miles southeast of Salt Lake City, just north of the mouth of the Big Cottonwood Canyon, a light gray-yellow, fine clay with very

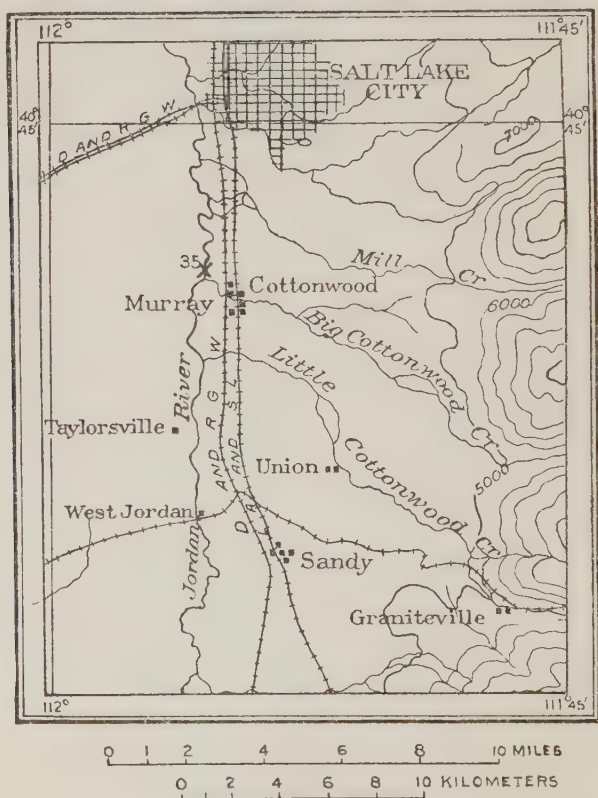
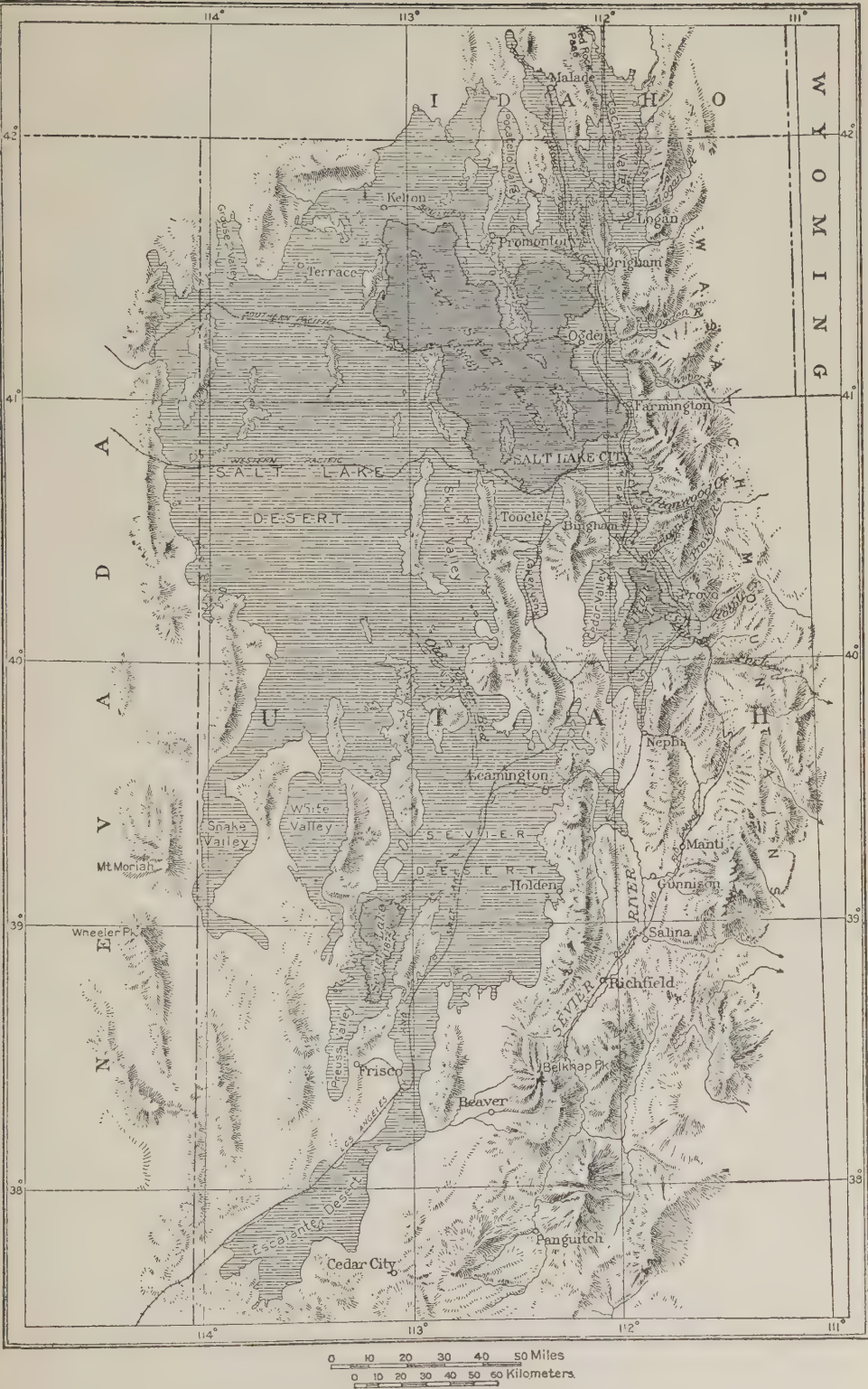


FIG. 16.—Map showing position of sections examined south of Salt Lake City, Utah.



LAKE BONNEVILLE, UTAH.
(From U. S. Geol. Survey, Monograph No. 1.)

indistinct lamination cropped out below the delta gravel; 1.5 miles north of Provo, on the river, a gray-brown, practically homogeneous clay was used in the brick industry.

North of Salt Lake City 15 miles, north of Lagoon or Farmington, there are on the electric railroad several long exposures of sediments up to 60 feet high. The beds are cream-colored and consist of alternating layers of silt and fine sand. The layers are from 0.33 inch to an inch thick. The meaning of the lamination is not clear. Just outside Salt Lake City, 0.66 mile north-east of the capitol, yellow-white silt and fine sand in alternating, wavy layers occur in gravel-pits above the Provo shore-line. Southeast of Salt Lake City 10 miles, on the highway a little north of the mouth of the Big Cottonwood Canyon, layers of yellow silt, 1 to 2 inches thick, were observed in alternation with laminae of fine yellow-brown sand, 0.3 inch to an inch in thickness. The sand layers are lens-shaped.

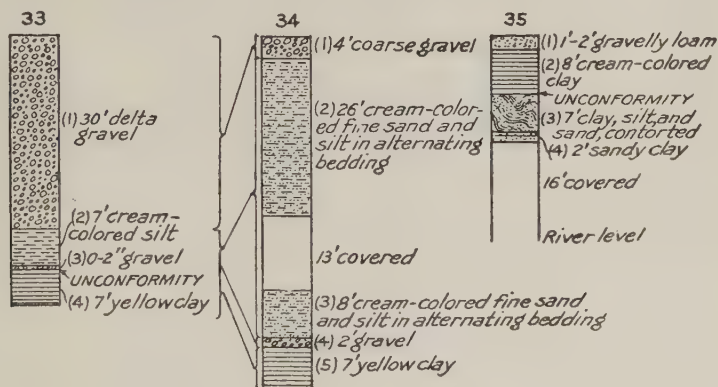


FIG. 17.—Profiles at Salt Lake City (33-35).

Profiles 33 and 34 show sections measured 700 and 800 yards respectively north-northeast of the capitol and above the Provo shore-line. In profile 33, bed 2 consists of cream-colored silt with thin laminae of fine, rusty sand. Bed 4 also contains thin layers of rusty sand and also small rounded pebbles. In profile 34, beds 2 and 3 probably are parts of the same bed; they are gray-yellow-white in color. In the upper part of bed 2 there occur some layers of white marl, 1 to 2 inches thick. These layers represent the only marl observed by the writer in the Bonneville sediments. Bed 4 contains cobblestones up to 5 inches in diameter. Bed 5 consists of yellow clay with laminae of rusty sand. The lamination, like that in profile 33, is very faint, and its meaning is not clear. Profiles 33 and 34 in all probability contain corresponding beds. The clay below and above the gravel-beds 3 and 4 in the respective profiles mark two stages when the lake-level stood above the Provo shore-line, and the gravel-beds indicate an intervening period when the water-level receded below it.

South of Salt Lake City 4 miles, on the west side of the Jordan River, north of the highway and 0.75 mile northwest of Murray railroad station, profile 35 was measured. Bed 2 is yellow to yellow-white. In the lower part it is laminated by thin layers of silt, but for the rest it is practically homogeneous.

Bed 3 consists of clay, silt, and sand in alternating layers, which mostly are entirely crumpled and contain scattered small pebbles. Stony unstratified clay and clayey gravel are kneaded into the stratified material. It appears as if water-soaked stony clay or clayey gravel had flowed over, disturbed and mixed with sandy water-laid clay. Bed 4 consists of layers of fine sand, 2 to 8 inches thick, alternating with laminæ of clay, 1 inch thick. Bed 3 indicates a stage when the water stood about as low as to-day.

PROFILES ON SEVIER RIVER.

The section near Leamington station, at the mouth of the Sevier Canyon and north of the river, was largely covered by talus, but, as far as could be observed, was just as described by Gilbert (1890, p. 192).

On the river, yellow, faintly laminated clays are exposed. On the railroad in the canyon, about 5 miles east-northeast of Leamington, an alluvial gravel with coarse boulders was observed below the clays. Of the clay, the lowest 2 feet showed a few distinct, probably annual layers, while the rest of the clay was only faintly stratified.

SUMMARY.

The exposures of Bonneville deposits examined register two lake stages with the water-level well above the Provo shore-line, which lies 625 feet above Great Salt Lake, or at an elevation of 4,824 feet, and one stage during which it receded to about the stand it holds to-day. This is the same result as reached by Gilbert (1890, p. 198) on examination of sections at Leamington and in the old river-bed, 75 miles southwest of Salt Lake City.

THE MONO BASIN.

The pleistocene deposits in the Mono Basin are well exposed in the western part, viz, in the canyons of the Mill and Rush Creeks, in some gullies, and on Paoha Island. The canyon of the Leevining Creek, at present, does not offer any exposures.

PROFILES ON MILL CREEK.

Profiles 36 and 37 show sections measured 1.33 and 0.75 miles above the mouth of the Mill Creek. The surface at profile 36 lies below the 6,000-foot curve, that is, about 500 feet below the Pleistocene shore-line of the lake. The gravels might be brought down by a brook or washed down by torrential rains, probably both. In any case, they indicate low stages of the lake. Because of the relatively steep grade of Mill Creek, material finer than gravel hardly can have been deposited along its course; therefore, the sandy, silty, and clayey beds are probably lacustrine, indicating that the lake reached at least above their horizons. The alternation of finer and coarser material in layers 2 to 5 most probably suggests oscillations of the water-level. Swings of the current of the brook over the shallow lake bottom, which could be thought of as a possible explanation, appear less probable. If sand layer 4, being only 8 inches thick, has not suffered erosion, it can hardly indicate any noteworthy change, but the clay layers 3 and 5 may best be regarded as one. If this be so, the profile marks two high-water stages and an intervening long, dry period during which the heavy gravel-sand bed was formed.

Profile 37 represents a lower horizon than does No. 36. The top gravel and underlying clay-silt bed probably are identical with the two lowest beds in



MAP OF THE PLEISTOCENE LAKE MONO, CALIFORNIA.

(From 8th Annual Report, vol. 1, 1886-87, U. S. Geol. Survey, Plates 17 and 29.)

profile 36. The sand, layer 4, shows ripple-marks, indicating its lacustrine origin. It probably marks a slight and short oscillation, so that beds 2 to 5 in reality together represent a single moist period. Bed 5, essentially consisting of clay-silt, particularly in its upper part, contains layers of fine sand which reach some feet in thickness. It also has a couple of layers of diatomaceous earth 0.5 inch thick, and finally two layers of gravel 1 and 2 inches thick respectively. The stratification is distinct because of variation in coarseness and color, but it does not show anything like varves.

The sediments exposed on Mill Creek seem to record two high-water stages and two stages during which the lake receded to about its present stand.

PROFILE SOUTH OF LEEVINING CREEK.

Profile 38 was measured in a gully cut by water escaping from an irrigation ditch, between Leevining and Rush Creeks and a mile from the lake. Beds 5, 6, and 7 evidently record a low-water period, whether they may essentially

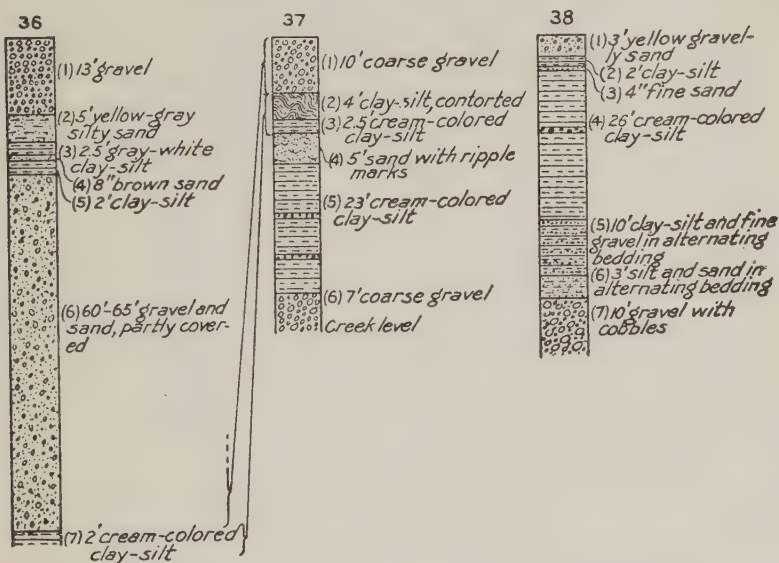


FIG. 18.—Profiles on Mill Creek and south of Leevining Creek (36-38).

be shallow-water or alluvial deposits. The clay-silt bed 4 contains streaks of fine sand, giving it a distinct stratification. In the middle of the bed there is to be found a gravel layer 1 inch thick. The bed shows great similarity to bed 5 in profile 37, and perhaps dates from the same moist period as this.

PROFILES ON RUSH CREEK.

From the junction of Bloody Creek with Rush Creek, 3 miles south of Lake Mono and for a couple of miles downstream, Pleistocene deposits at many points are well exposed.

Profile 39 was measured just below the junction of the creeks, 300 yards northeast of the fault-line (see Russell, 1889, plate 22, p. 302) on the south side of the canyon, and profile 40 at 100 yards below No. 39. The correlation of the different beds became more or less evident in the field, and is partly shown

in figure 19. The most noteworthy feature of the sediments is their frequent vertical change and the dominating rôle played by relatively coarse material. The rapid change of the beds in a horizontal direction also is remarkable. The profiles, as stated above, lie only 100 yards apart.

When interpreting the profiles, consideration, in the first place, must be taken of their position directly below three streams rushing down a steep grade. The coarse gravels could be, and perhaps partly were, deposited in the brooks, but the great bulk of the sediments no doubt was laid

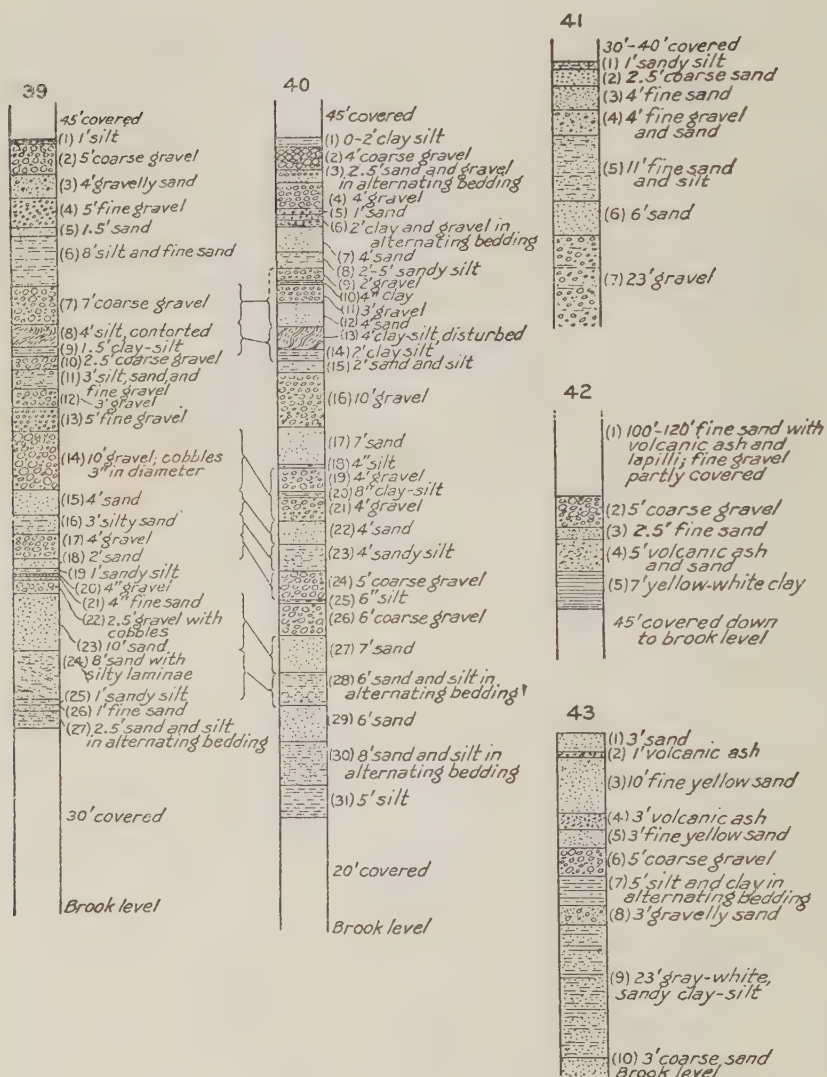


FIG. 19.—Profiles on Rush Creek (39-43).

down in the lake during a stage of higher water than to-day. Practically all of the beds indicate shore or shallow-water conditions. The frequent alternations of coarse gravel, fine gravel, and sand may be largely due to small fluctuations of the lake-level and changes in the strength and direction of the currents of the brooks.

The silt and clay-silt layers, which with two exceptions are very thin and rapidly wedge out, seem to be open to different explanations. They might mark risings of the lake-level of some length and extension, though waves and currents during the subsequent sinking transported all but insignificant parts of the deposited clay into deeper parts of the lake. The occurrence of oscillations of the lake-level during the deposition of the beds is practically certain. On the other hand, clay-silt layers so thin and of so little extent perhaps could have been deposited in shallow water during swings of the currents of the brooks. The thick clay-silt bed in the upper part of the sections, layers 8 and 9 in No. 39 and 13 and 14 in No. 40, in any case must mark a high-water stage of the lake. Disregarding alternation of gravel and sand beds, etc., the sediments keep practically the same coarseness throughout the sections, which are more than 100 feet deep. This shows that the deposition eventually took place during a rising of the lake-level, and kept even pace with this. The lake which was low because a large part of the precipitation of the basin was stored in glaciers, eventually rose as the glaciers melted. The waters brought the débris of the glaciers, and so the deposition of clastic material took place largely as the glaciers receded. It is, however, perhaps more likely that the lake stood high when the glaciers were large, that the sedimentary records are very incomplete, and part of the beds were formed through redeposition during the time following the last maximum stand of the lake. The time of the deposits, on the whole, is uncertain, and it is not known how much eventually represents earlier glacial epochs.

Profile 41 was measured 500 yards northeast of profile 40. In spite of its nearness to profile 40, this section can not be connected with the latter, a good illustration of the rapid change in a horizontal direction. The beds seem to be all shore and shallow-water deposits.

Profile 42 was measured a few hundred yards north of profile 41. The clay-bed evidently was deposited in relatively deep water and the other exposed beds in shallow water or at the shore. The beds of lapilli and volcanic ash show that the adjacent volcanoes were then active. This profile, as little as section 43, is correlated with those farther up the stream.

Profile 43 was measured 150 yards north of profile 42. The clay-silt, bed 9, contains layers of fine sand with ripple-marks showing that the bed was deposited in comparatively shallow water. It also has thin layers of volcanic ash and of white diatomaceous earth. The other beds, with the exception of bed 7, may have been deposited near or at the shore, or the gravel perhaps above the lake-level during a period of low water. In any case, the sediments indicate some slight oscillations of the lake-level.

The sediments on Rush Creek record a general rising of the lake, interrupted by several slight oscillations. They also register two or perhaps several high-water stages and one to more stages with the lake-level only slightly above that of the present.

PROFILES IN PAOHA ISLAND.

Almost the entire Paoha Island is composed of Pleistocene lake sediments which are highly eroded, so as to form a badland topography. The sediments consist of fine material, largely clay. Diatomaceous earth also plays a great rôle, particularly in the higher parts. The thickness of the remaining sediments is unknown, but may be 200 to 300 feet. The clay is mostly fine and dense, with bands of silt. It does not show any lamination which can be seasonal. In moist condition it is dark gray-brown, in dry condition gray-white. The diatomaceous earth, which occurs in beds, according to Russell (1889, p. 319) up to 30 feet in thickness, is white with dense, thin, dark streaks, so that the beds resemble the cross-section of wood. The lamination perhaps is annual. The following section, measured in the central, highest part of the island, gives an idea of the alternation of clay and diatomaceous earth:

- Topmost, thick clay bed.
- 16 inches diatomaceous earth and clay, equal parts of each.
- 4 inches clay with some diatomaceous earth.
- 16 inches almost pure diatomaceous earth.
- 6 inches clay.
- 4 inches diatomaceous earth.
- 8 inches clay.
- 6 inches diatomaceous earth.
- 4 inches clay.
- 3 inches diatomaceous earth.
- Covered.

The clay-beds in the island are greatly disturbed, literally broken into pieces which have moved in relation to each other, so that the strata in some blocks dip considerably. One observed fault amounted to 12 feet. Such disturbances were observed by Russell (1889, pp. 389, 390).

As Russell (1889, pp. 372-377) pointed out, Negit Island, the craters, and the lava coulée at the northern end of Paoha Island, as well as other volcanic formations on the lake, are of very recent date. In fact, those in Paoha Island were formed since the lake fell to its present level. To this can be added that the whole Paoha Island probably is a raised block, pushed up since the deposition of the sediments of which it consists; in other words, since the last high-water stage of the lake. The fine clays in the island reach more than 200 feet above the level of the lake, which south of the island is more than 150 feet deep. Although the fineness of the material permitted this to remain well suspended, it is highly improbable that the clay could be deposited on the top of a projection, for the violent winds descending from the Sierra agitate the lake to an incredible degree, so that it surely would have been washed down into the deeper parts of the lake. Now the island is being rapidly cut away by the action of the waves. The faults and other disturbances of the clay-beds also show that, in rather recent time, the island has been very unstable.

VII. PLEISTOCENE HISTORY OF THE GREAT BASIN.

Of the Pleistocene history of the Great Basin the broad lines seem clear and many details are well known. The chief events practically certainly have been parallel with the large events in the northern part of the continent. In the North, four or possibly five glacial epochs, separated by warm interglacial periods, have followed each other. In the Great Basin glaciations combined with expansions of the waters have alternated with arid periods. The high-water stages were due to heavier precipitation than at present and to little evaporation because of low summer temperature. The relatively heavy rainfall was connected with the changes of climate that checked the expansion of the ice-sheets and caused the ice-fronts to retire. It was a consequence of decrease of precipitation over the land ice possibly caused by rise of temperature. The mountain glaciations and the slightly lagging high levels of the lakes in the Southwest were contemporaneous with the climaxes of the great glaciations and the early stages of ice retreat. The arid periods corresponded to the interglacial epochs. The pink, brown, or rusty colors of many old beds may indicate more pronounced desert conditions than now prevail. While red beds are now forming in the centers of the great deserts, such as the Tarim and the Transcaspian deserts (Huntington and Visher, 1922, pp. 151, 170), all deposits under formation in the deserts of the Southwest are creamy-white. Red beds, according to Barrell (1909, pp. 285, 292), are due to alternation of seasons of warmth and dryness with seasons of floods. Oxidation is found to be particularly strong in deserts after rain (Walther, 1912, p. 24). In the mountains of the Southwest records of three glacial epochs have been recognized, and in the basins sedimentary records of three or perhaps four lake stages are known at present. Doubtless there were in the Southwest as many glaciations and high-water periods as there were glacial epochs in the North, and the last ones corresponded to the last glacial epoch, that is existed 30,000 to 35,000 years ago.

As the ice-sheets disappeared an adjustment of the climatic conditions took place, through which the belt of heavier rainfall again shifted northward. Shore-lines below the highest level of the Pleistocene lakes and alternations of beds of different coarseness indicate stationary lake-levels and small fluctuations during the general fall of the waters. In relatively recent time Walker Lake and perhaps Winnemucca Lake have been dry, and the other lakes also may have stood essentially lower than at present (cf. pp. 65, 66, 102).

LAKE LAHONTAN.

The Pleistocene deposits of the Lahontan Basin, so far as they are exposed, seem to record three or perhaps four distinct moist stages, during which the valleys were flooded by deep waters, with preceding and intervening arid periods during which the water-level receded to about the present stand or even farther. Besides, they record oscillations of lesser amplitude. The fresh-water molluscan faunas of the lake-beds (Call, 1884) may show that the waters of the basin were freshened repeatedly during the long era represented by the exposed deposits.

All the shore-lines seem to belong to the last expansion. The thinolite terrace, according to Jones (1925), at places is cut in rock, and probably was developed before the last lake reached its maximum height. All the other shore-lines are developed only in loose material and may date from the fall of the water-level (Jones, 1925).

The dendritic and lithoid tufas, according to Jones's recent study, were formed through the activity of algæ. The dendritic tufa was formed in light and favorable situations, the lithoid tufa in dark and less favorable places for the growth of the algæ. The thinolite tufa may have been precipitated when the lake was practically saturated with calcium carbonate. The two first-mentioned kinds of tufa no doubt, and all three kinds possibly, could have been formed simultaneously. The bulk of the tufas dates from the closing period of the Lahontan stage.

No detailed study attempting to connect the shore-lines in the Lahontan Basin with shore-lines in other basins has been made.

Of events in post-Lahontan time the freshening of the waters is of particular interest. The low salinity of Pyramid, Winnemucca, and Walker Lakes demonstrates that the present conditions can not have existed for a very long time. The other lakes in the Lahontan Basin are of no interest in this connection. Of these, Honey Lake and North Carson Lake become completely desiccated during unusually dry summers (Russell, 1885, pp. 55, 68), and Humboldt and South Carson Lakes normally overflow into North Carson Lake. The salinity, in 1882, in Pyramid Lake was about 0.35 per cent, in Winnemucca Lake 0.36 per cent, and in Walker Lake 0.25 per cent (Russell, 1885, pp. 57, 58, 63, 70). The freshening of Pyramid and Winnemucca Lakes can have taken place by overflow through Emerson Pass into the Smoke Creek Desert, whose floor lies 20 feet below the surface of Pyramid Lake, and perhaps further overflow to the Black Rock Desert, where the water evaporated and the deposited salts became buried under playa clays. The pass-point lies about 70 feet above Pyramid Lake, and the outlet channel is well defined (Gale, 1915, p. 210; Huntington, 1915, p. 235). The Smoke Creek Desert and the basins north of it have no present perennial water-supply, and there is, as Gale points out, little doubt that their waters during the Lahontan stage came largely from the Truckee River. Owens Lake in California overflowed 4,000 years or less ago (Gale, 1914, p. 264). Jones (1925, p. 41) considers this alternative to be out of question. The freshening can also have occurred through overflow of Pyramid Lake into Winnemucca Lake and desiccation of the latter lake, as discussed by Dr. Huntington in the following paper, provided it can be assumed that the fish fauna in the lakes could survive such an event; for the fish fauna in the Lahontan drainage system may go back to Lahontan or pre-Lahontan time, as most of the fishes are distinct from related forms elsewhere (Snyder, 1915-16, p. 39). One genus, *Leucidius*, is restricted to the system, and *Chasmistes cujus* and *Salmo smaragdus* are known only from Pyramid and Winnemucca Lakes.

Walker Lake, which is about 225 feet deep, while Pyramid and Winnemucca Lakes are 361 and 87 feet deep, respectively (Russell, 1885, plate 15, p. 70; plate 9, p. 56), in any case, must have been desiccated and the salts buried a few thousand years ago, for it has not, like Pyramid and Winnemucca Lakes, any adjacent evaporation-pan through which to become freshened.

LAKE BONNEVILLE.

In the deposits of the Bonneville Basin, which unfortunately lack good exposures, so far only two high-water stages with the water-level above the Provo shore-line, 625 feet above Great Salt Lake or 4,824 feet above sea-level, and a dry period during which the water receded to about its modern level, are found, though there must have been more. To the history, as interpreted by Gilbert, little of importance can be added. It seems likely that not the Bonneville stage, but the early part of the Provo stage, though this was lower since the lake cut down an outlet channel, coincided with the moistest time.

LAKE MONO.

The deposits exposed in the Mono Basin seem to record two or perhaps several high-water stages and two or more stages with the lake-level only slightly above that of the present. The deposits, however, may form only an incomplete record, since the substratum is nowhere reached and some beds probably have suffered complete or partial erosion.

CONVERSION TABLES.

Inches converted into centimeters.		Feet converted into meters.		Miles converted into kilometers.	
Inches.	Centimeters.	Feet.	Meters.	Miles.	Kilometers.
1	2.540005	1	0.3048006	1	1.609347
2	5.08	2	0.6096	2	3.22
3	7.62	3	0.9144	3	4.83
4	10.16	4	1.2192	4	6.44
5	12.70	5	1.5240	5	8.05
6	15.24	6	1.8288	6	9.66
7	17.78	7	2.1336	7	11.27
8	20.32	8	2.4384	8	12.87
9	22.86	9	2.7432	9	14.48
10	25.40	10	3.0480	10	16.09
11	27.94				
12	30.48				

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THE BIG TREE AS A CLIMATIC MEASURE.

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One Plate and Seven Text-figures.

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THE BIG TREE AS A CLIMATIC MEASURE.

INTRODUCTION.

Exact meteorological records nowhere existing for a much longer period than a century, and in most places only for a considerably shorter time, scientists have long sought natural meteorological measures extending farther back. The annual growth-rings in trees were early considered but it was not until Professor Andrew E. Douglass, of the University of Arizona, in 1901 took up the study, that positive results were obtained. Dr. Douglass made ring measurements on the yellow pine (*Pinus ponderosa*) in the arid region of northern Arizona, and found direct relation between width of growth rings and precipitation. In 1911, Professor Ellsworth Huntington, of Yale University, began his measurements on the big tree (*Sequoia washingtoniana*) in the Sierra Nevada in California, which, since corrections for non-climatic factors had been applied, enabled him to construct a climatic curve reaching 3,000 years back. The results obtained by Dr. Douglass and Dr. Huntington are of great and many-sided importance and have increased our knowledge of climatic periodicity particularly.

The studies had reached the point where the need of detailed analyses of the factors influencing growth, of easily applied methods of correction, etc., made themselves felt, and therefore this restudy of Dr. Huntington's sequoia material has been carried out under the auspices of the Carnegie Institution of Washington at the request of its President, Dr. John C. Merriam.

The study has been made possible by Dr. Huntington's generosity in placing all his original material and annotations at the writer's disposal. During the course of the investigation at Yale, Dr. Huntington has aided in word and deed. The Departments of Geology and Biology, as well as the library of Yale University, have shown the greatest hospitality. Dr. D. T. MacDougal, of the Carnegie Institution of Washington, has kindly read the entire manuscript and made valuable suggestions, and, together with Dr. Forrest Shreve, of the Carnegie Institution, has allowed the writer to use part of their unpublished studies on the relation between the growth of the Monterey pine (*Pinus radiata*) and precipitation. Professor Robert DeC. Ward and Dr. I. W. Bailey, of Harvard University, have given much valuable advice.

OCCURRENCE OF THE BIG TREE.

The big tree or giant redwood (*Sequoia washingtoniana* [Winslow Sudworth]), largest and longest-lived plant in existence, occurs in a narrow strip of land between the thirty-sixth and thirty-ninth parallels, on the western slopes of the Sierra Nevada in central California (Huntington, 1914, p. 141; Sherwood, 1915; our fig. 1). It grows at altitudes between 5,000 and 7,000 feet (1,500 and 2,000 meters), rarely going below or above these

limits. In the belt in which the sequoia grows the annual precipitation is greater than in the belts above and below (cf. Henry, 1919, p. 39) and is abundant, probably averaging between 30 and 50 inches (750 and 1270 mm.) (McAdie, 1914, pl. 21; Ward, 1917). Only very short meteorological observations, however, exist from this region. Of the precipitation, by far the greater part comes in the form of snow during the months December to March. The rainfall during April to September, during the growing-season, is only a few inches and the water runs quickly down the slopes. The winters are intensely cold, but the summers are mild.

The mountains in the regions where the giant redwood lives are generally rugged, with steep slopes. The basins between the ridges collect the water of the melting snow, and in spring and early summer become very swampy. The sequoia grows in the valley bottoms as well as on dry ridges. It requires sunlight and sandy soil from which the leaf mold has been removed (Sherwood, 1915, p. 7).

"For this reason there are practically no seedlings in the shadows of the untouched northern groves, but wherever in the southern groves lumbering and fire have opened up the forest and exposed the mineral earth, an abundance of young Big Trees is always found near seed trees."

Huntington (1914, p. 152) found young trees to be abundant in moist places such as valley bottoms, flat ridges, and hollows where moisture accumulates or runs through deep soil.

MATERIAL.

The material used for the construction of the curves was collected by Huntington and his assistants in 1911 and 1912. Most of it was derived from a circle 10 miles (16 km.) in diameter, centering between Hume and the General Grant National Park, particularly from the Indian and Converse Basins; but a considerable part comes from a region 40 miles (64 km.) farther south, from the tract just south of the Sequoia National Park, or about 13 miles (21 km.) northeast of Springville (Huntington, 1914, pp. 142, 144). Huntington measured trees living under all conditions, trees growing on dry ridges as well as on moist places or even in water. He made the measurements directly on the stumps, and measured successive groups of ten annual rings. He measured the average or the best radius and generally two or three radii on each stump. The material used here is that from which Huntington calculated his climatic curve published in *The Climatic Factor* (our fig. 7). Huntington's curve is based upon all his material, consisting of 451 trees or 785 measurements. Here have been selected, of the trees measured by Huntington, on the one hand, those growing on more or less dry ridges, high above water, and on the other hand those living in the moist bottoms of the valleys, in or close by water. The trees of these two groups have been treated separately and climatic curves calculated. Also a general curve has been constructed from both curves. Besides, a curve based on all Huntington's material has been calculated in a somewhat different way.



View of Sequoia Forest. (Sherwood.)

The falling tree is nearly 1,400 years old; the stump is 90 feet in circumference.



TIME AND COURSE OF GROWTH IN THICKNESS.

Knowledge of the time and course of radial growth of trees is evidently important when studying the climate of the past by means of the varying widths of the annual rings. In every particular this is the case when summer rains are lacking, so that all growth is dependent on the precipitation during the preceding winter, or when rains during the growing season are scanty or limited to certain periods.

The time of activity of the cambial initials has long been given considerable attention (see Antevs, 1917, pp. 334-346), and in later years particularly it has been studied by MacDougal (1921) and Shreve.¹ Studies of the question have been carried out in different ways. Some students, at certain intervals, have cut trees of the same age and of similar conditions

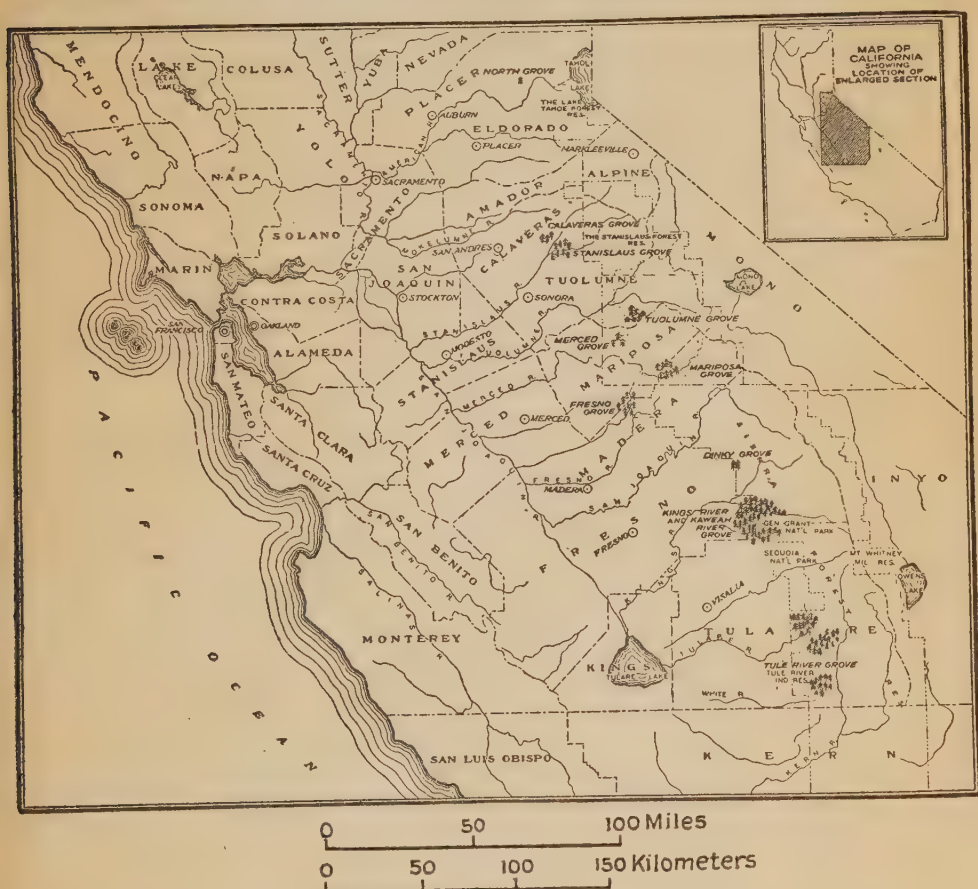


FIG. 1.—Distribution of the Big Tree. (Sherwood.)

of life, or have taken bore samples in the same trees. Others have removed branches and twigs. Still others have from time to time measured the circumference or the diameter of the trunk. MacDougal and his associates

¹ Unfortunately the latest papers by MacDougal (1924) and Shreve (1924), so important for the discussion of tree growth and climate, came too late into the writer's hands to be duly considered.

have measured the diameter by a self-registering apparatus, the dendrograph, and by a simpler dendrometer.

Each one of these methods has its weak sides. Different individuals show considerable differences regarding time of cambial awakening and progress of growth. The wounds after the borings stimulate growth in the vicinity of the bore-holes. In spring, before formation of wood elements begins, a swelling of the cambium zone occurs. The radial growth ceases quite gradually.

The awakening of the cambium begins earlier than, contemporaneously with, or later than the bursting of the buds, that is at the end of April and during May in northern Germany and southern Scandinavia and one or two weeks earlier in the northern parts of the United States. As a rule, the difference in time between the two processes is slight, but occasionally it amounts to a whole month. Generally the cambial activity starts in the youngest twigs. The differences in time between the cambial awakening in the twigs and at the base of the trunk sometimes is insignificant, or sometimes rather great, amounting to as much as four weeks. Often, though, the awakening takes another course.

In Europe the intensity of the radial growth, in the beginning, is relatively weak, but it increases rapidly and generally reaches a maximum in June or July. Thereafter it diminishes gradually until the wood formation ceases in the autumn; or it drops to a minimum, rises to a second maximum, and then finally falls. In cases studied by MacDougal (1921, p. 5), the activity of the cambial initials depends upon environmental conditions, and no observations suggest a seasonal rhythmic action. Desiccation of the soil in the dry fore-summer can stop the growth, which, however, starts anew, consequent upon summer rains or irrigation, and continues till checked by decreasing temperatures and increased soil desiccation in the autumn.

In Germany the woody ring, as a rule, is finished during the month of August or the early part of September, seldom later, that is, after three to four months. The greater part of the annual ring, however, is already formed at the end of June, or about two months after the beginning of the cambial activity. The formation of wood ceases at different times in different parts of the tree. The order can be the same or different from that in which the awakening of the cambium takes place. (See also MacDougal, 1924, pp. 5, 81-86; and Shreve, 1924, pp. 95, 116.)

VARIATIONS IN WIDTH OF GROWTH-RINGS, AND ANOMALOUS RINGS.

The width of annual rings is influenced by inherent factors and by a number of external causes of climatic and non-climatic nature, such as precipitation, temperature, solar radiation, windiness, soil, shading, liberation, abundant seed production, defoliation or injury caused by insects, fire, frost, wind, falling trees, animals, etc. The normal total growth period and most important variations and anomalies as well as their causes will be briefly considered here. References to the extensive literature will be found in an earlier paper by this writer (1917, pp. 318-333).

THE GRAND GROWTH PERIOD.

Growth is first dependent on internal conditions; trees go through childhood, youth, maturity, and old age. A sapling, as a rule, has a very limited power of growth, and the innermost growth-rings are narrow. The tree gradually gains in strength, and the width of the annual rings increases as the crown is augmented. Sooner or later the width reaches a maximum, which occurs at different ages in different species and individuals; in European trees generally at ages from 10 to 75 years, and in the yellow pine at 35 years of age (Huntington, 1914, p. 128, fig. 28). The maximum is either maintained for some time, or decrease sets in immediately. The diminution can be rapid or gradual. The big tree forms an exception to the rule, as the innermost rings generally are thickest (Huntington, 1914, fig. 36, p. 151; our fig. 2). In many specimens, however, the innermost rings are quite narrow. The rings then increase in width for 100 to 300 years, reach a maximum, and decrease. In many other

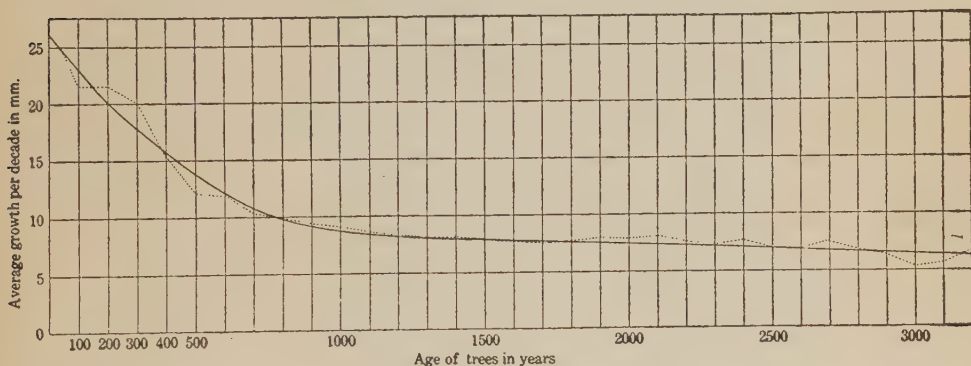


FIG. 2.—Corrective factor for age. (Huntington.)

individuals the innermost rings are wide and maintain the width unchanged for a few hundred years, whereupon diminution begins. Whether these differences are characteristic of individuals, or of different races within the species, or depend on external factors, such as shading during youth, is not known to the writer. As seen in figure 2 the width of the annual rings in the giant redwood decreases rather rapidly till 700 years of age, then gradually until 1,300. From the age of 1,300 to 2,100 the growth curve is practically horizontal.

The growth on the whole records the changing vitality or energy of the tree during its life-stages. This changing vitality is to be kept in mind, since the influences of the external conditions upon the growth on the whole may stand in reversed relationship to it. It is a well-known fact that young, vigorous trees are relatively far less influenced by external conditions than are old individuals. The variations of the growth curves of the sequoia are relatively much less in the highest part of the curves than in the lower portions (Huntington, 1914, fig. 26, p. 125). Rings formed when trees are very old may for several reasons not be good.

The best material of the big tree may be the parts deposited during the age from about 1,000 to about 2,000 years. To this material little or no correction has to be applied, and the trees are still strong and vigorous.

FLARING.

Trunks of trees are thickest at the base. In the huge stems of old sequoias the flaring is considerable and reaches a height of 15 to 20 feet above the ground (Huntington, 1914, p. 154). Since the ordinary height of the stumps on which the ring measurements were made by Huntington was only 5 or 6 feet, and sometimes not more than 3 or 4 feet, flaring evidently causes the growth rings in the old parts of the trees to be measured at an outward increasingly oblique angle so that the measured widths gradually grow outward; in other words, flaring causes the ring curves to rise toward the present time.

ECCENTRICITY.

While theoretically normal, concentric growth in reality is the exception, for it postulates that branches, foliage, and roots are uniformly developed on all sides, and that nourishment, light, and wind also are the same on all sides. The favoring of one side is balanced by reduction of another side. In extreme cases no cells are set off on one side, so that the growth rings wedge out.

In the giant redwood eccentric growth is rather common. From being about equally great along different radii, the growth can be favored on one side and amount to more than twice the normal growth. Since only about half of the surface of the stumps is sufficiently smooth, measurements from directly opposite radii were seldom or ever made. Along other radii, the contemporaneous growth can decrease, which is most common, remain normal, or increase. The eccentric growth can last for several decades. Thereafter the growth generally again proceeds at about the same rate on the measured radii, or else the radius previously favored may decrease slowly and the previously suppressed radius may be favored. The changes can be gradual, but more often they are sudden. The greatest and most abrupt alterations as a rule last for the shortest time. Sometimes the eccentricity is caused by growth reduced below the normal on one side. Often the eccentricity leads to omission of rings on one side of the tree, particularly in constant eccentric growth, caused by the habit of the sequoia of growing in clumps, by which the inner sides become suppressed (Huntington, 1914, pp. 143-149).

Eccentric growth has been rather extensively studied by European botanists in recent years, but satisfactory explanation of all cases has not yet been given. Eccentricity is caused by one-sided influence of factors, such as light, heat, gravity, wind, pressure, stretching, and torsion. According to Jaccard (1919, pp. 177-189), the factors influence the nourishment and hence the osmotic conditions of the cambial initials, which in their turn determine the rate of cell formation and the character of the cells. Light and heat can both stimulate and check the activity of the cambial cells. Stretching and pressure caused by bending, etc., check the activity of the cells in the plane of bending and stimulate in a corresponding degree the initials on the flanks, because these latter attract the nutritive solutions.

There are, however, cases which do not fall under this explanation. Ursprung (1906, pp. 264, 265) quotes from different authors cases in which growth is strongest on the side opposite the wind or even on both sides of the trunk in the plane of bending. The advantage is apparent, but the facts await explanation. One of the most common cases of eccentricity, or the favoring for a short period of now this, now that, side may be connected with sudden changes in environment or with injuries.

DOUBLING OF RINGS.

The term "double ring" indicates a woody mantle deposited during one season but more or less resembling two normal annual rings. On one side the anomaly may be almost imperceptible and on the other side the double ring may so completely resemble two normal rings that not even the microscope can reveal any difference. This latter case, however, is very rare, and as a rule the doubling is easily detected or can be discerned by a closer examination.

The extension of doubling is dependent primarily upon the extent of the conditions causing the anomaly. As a rule, it is limited to young or even the youngest twigs, and is not known to embrace the whole tree. In the parts of the tree lacking doubling the growth-ring is normally developed.

Generally the doubling is caused by anomalous sprouting, since the cambial initials have been in activity for some time. Anomalous shoot formation before the awakening of the cambium evidently has no effect; but, as soon as spring wood with wide elements is formed, doubling may enter, for autumn wood may be deposited during the time between the injury and the anomalous sprouting. Anomalous or "echte proleptische Triebe," says Späth (1912, p. 31), "sind solche, die sich ohne Rücksicht auf die Jahreszeit an einem belaubten, unversehrten Spross unregelmässig nach völliger Beendigung des Längenwachstums, also aus bereits geschlossenen (fast nur terminalen) Knospen nach einer ausgeprägten Ruheperiode entwickeln." On the other hand, all normal shoots developed after the shoot formation in spring, as sylleptic shoots and "Lammas shoots," have no other effect upon the radial growth than an increase.

Anomalous shoot evolution can occur without or after injury. Sprouting of the first kind particularly takes place at the end of the summer. It is caused by favorable nutritive and climatic conditions, especially after chilly weather. It is a rather unusual thing. In the latter part of the summer of 1910 anomalous sprouting was common in Sweden and in Germany. Proleptic shoot formation of the second kind generally arises as a consequence of defoliation, decapitation, or injury of the terminal buds by insects, frost, drought, storms, or the like. Time and extent of the proleptic sprouting and climatic conditions, as stated above, are decisive for the development and extension of the doubling. Anomalous shoot evolution, after the normal woody ring is fully developed, and favorable growth conditions till late in the autumn, may produce a double ring, perfectly resembling two normal rings.

Ring doubling was observed by Shreve (1917) in the Chihuahua pine (*Pinus chihuahuana*) and by MacDougal (1921, pp. 21, 22) in the Monterey pine as a consequence of summer or autumn rains, or of irrigation giving

new energy to the growth checked by desiccation of the soil. Ring doubling in the yellow pine in Arizona is ascribed by Douglass (1919, p. 18) to similar causes. Doubling can also enter without proleptic sprouting. This is known to have taken place in different conifers after frost injury of the cambial zone. The formation of a second ring consequently is connected with sprouting or renewed lively growth after a condition of complete or relative rest of the cambial initials, during which no cells or narrow elements resembling autumn wood were formed. Triple rings also occur occasionally.

OMISSION OF RINGS.

Just as growth rings may be supernumerary, so also may they be less than normal in numbers. They are dropped most often in strongly suppressed, slow-growing individuals during unfavorable years, but also after strong disturbances of the integrity of the trees, as defoliation, unfavorable weather conditions, lack of light, etc. MacDougal (1921, p. 7) states that of 15 trees which were under dendrographic measurement in 1920, one each of three species made no enlargement during the year. One-sided omission in strongly eccentric trunks is quite common. In most cases dropping is limited to the lower part of the trunk. The number of elements decreases till the ring wedges out; but growth may also fail in the entire tree. The normal cause of dropped rings is insufficient nourishment.

The outwedging ring consists of normal autumn-wood elements. The cambial initials may remain alive for decades without forming new cells, in order, under favorable nutritive conditions, to begin anew to set off cells.

ABUNDANT SEED PRODUCTION.

Abundant production of seeds causes a reduction of the radial growth during the seed year. The decrease in growth may extend to the following year and then be greater than during the seed year itself. In some cases the reduction of growth is found to be limited to the youngest twigs. The probable cause of the reduction is that the nutrients, in the first place, are used for the production of the fruits, so that the cambial initials are inadequately nourished. It has, however, been maintained that the nutrition is not insufficient, but that the growth of other tissues than wood is favored in the fruit-bearing twigs.

Abundant seed production is periodic and must be taken into consideration when studying climatic periodicity by means of tree-growth. In the Scotch pine it occurs every 5 or 6 years, or just twice in a sunspot cycle, whose length is 11.2 (Wolfer, 1820, p. 459) or perhaps 11.4 years (Douglass, 1919, p. 84).

SHADING AND LIBERATION.

Growth is very slow in shaded trees because of lack of light and nourishment. The cambial initials often become quite functionless in the lower part of the trunk, and occasionally in the whole of the stem. If by cutting of the shading trees a suppressed tree is given a chance, the rings in the lower part of the trunk at once increase in width and can reach twice the normal size. In the upper portion of the trunk, on the contrary, the ring width remains unchanged or even diminishes. The change in the

amount of growth may take a very different course, according to the soil and other conditions. A maximum of growth may be reached during the first year, after 4 or 5 years, or after several decades. When the maximum is reached, gradual decrease begins at once or after several years. Some years later the ring-width is reduced to the normal amount. In European trees the increase in growth generally lasts 10 to 15 years.

The chief cause of the intensified growth is considered to lie in greater inflow of nutritive substances from the soil, whose humus is rapidly decomposed by the direct influence of the atmospheric agents. It is perhaps probable that the assimilation is increased, but it is noteworthy that the foliage does not increase. When the supply of the nutrients of the soil is consumed, and when a new stand has grown up and previous conditions of nourishment and shading have become restored, growth has diminished to its previous amount.

The concentration of the growth in the lower part of the trunk can not be explained, but it is an observed fact that disturbances and injuries influence growth considerably in the lower part of the trunk, but only a little or not at all in the upper portion.

DEFOLIATION, TOPPING, ETC.

While the loss of a small part of the foliage generally does not do any harm, a defoliation or decapitation carried too far may kill the tree. As a rule, defoliation reduces the growth for a number of years. The ring formed during the year of operation may be normal, or wider, or narrower than normal; sometimes it is double. Often this ring, as well as those of the following years, wedges out toward the base of the trunk, where, as mentioned, the effects are felt most. In the upper part of the trunk the rings generally also are reduced, but cases are known where they have increased in width.

The extent of the operation necessary to influence the development of the growth rings varies in the first place with the size of the crown of the tree. Free-standing trees have been deprived of one-half of the foliage without any effect on the growth during the following years. With trees growing in thickets and having few or no surplus of leaves, on the contrary, a diminution of one-fourth to one-third of the foliage causes reduced growth. The decrease in growth is commonly attributed to insufficient nourishment. During the year of defoliation all or the greater part of the food reserves are consumed, and when all reserves are used up the growth falls to a minimum, from which it rises at the same rate as the tree recovers and the foliage increases. After 5 to 20 years or so the growth is again normal. (See also MacDougal, 1924, p. 82.)

PRECIPITATION.

The width of growth-rings is influenced by precipitation, temperature, and radiation of the sun. Warmth and abundant supply of nutrients and water are commonly regarded as the essential requirements for rapid growth, but recent studies appear to indicate that variations of the sun's radiation also are of great importance. The combination of these factors may be manifold and their effects varying, depending on different conditions,

so that an analysis of the rôle played by each is always difficult and in the case of the big tree not possible, since necessary data do not exist.

As a general rule, the growth of trees which live under such conditions that they are easily affected by drought is determined first by precipitation. They deposit wide rings during rainy years and narrow rings during dry years. The best example is the yellow pine in the arid regions of Arizona, so carefully studied by Douglass (1919, pp. 65-70). Too much moisture generally checks the growth, not only directly but also indirectly, because unusually rainy summers in the greater parts of the temperate regions as a rule are also chilly. Thus, in Sweden the radial growth of the Scotch pine almost reached a minimum during the rainy and chilly summer of 1902 (Hesselman, 1904). It is noteworthy, however, that the coast redwood (*Sequoia sempervirens*) requires little of the soil but that it contain moisture, of which it can not get too much (Fisher, 1903, p. 12).

Besides the amount of precipitation, the time of its coming is of great importance. The rain which falls during the growing period, during May to July, means most. On the other hand, the precipitation during the months preceding the growth in Schwartz's (1899, p. 129) mind is without effect upon the Scotch pine in Germany. In the arid regions of Arizona, which lack or have little rainfall between winter and July, snowfall plays a great rôle for the growth of the yellow pine (Douglass, 1919). The same is true for the home of the giant redwood, whose growth is almost exclusively dependent on the precipitation before the growing-season. As will be discussed later, growth of both of these trees is to some degree also dependent upon the precipitation of a number of preceding years. (See also MacDougal, 1924, pp. 81-861; and Shreve, 1924, pp. 106, 116.)

In the yellow pine, Douglass (1919, pp. 67, 71) found a yearly agreement without lag between growth and precipitation and in long periods an agreement with lag of about 4 years. The annual precipitation has with the greatest advantage been calculated from September 1 at Prescott and from November 1 at Flagstaff. (See also Huntington, 1925.)

As stated by Douglass in 1919 (pages 66 and 68):

"The accuracy with which the pine trees near Prescott represent the rainfall in that city for 43 years is, without correction, about 70 per cent. By a provisional correction for conservation of moisture by the soil this accuracy rises to about 82 per cent. The nature of this conservation correction is very simple, it makes use of the 'accumulated moisture' of the meteorologist. It signifies that the rings in these dry-climate trees vary not merely in proportion to the rainfall of the year, but also in proportion to the sum of the profits and losses of the preceding years." "The variations in the Prescott trees were seen to be proportional both to the rainfall of the year and to the average growth or activity which the trees had exhibited in the preceding few years. But this average growth bore the same relation to the average or smoothed rainfall that the accumulated moisture bore to the smoothed rainfall. Hence the ratio between accumulated moisture and smoothed rainfall gave at once the required ratio between smoothed tree-growth and smoothed rainfall."

The relation between precipitation and growth of the big tree has been treated at considerable length by Huntington (1914, pp. 157-174; 1922, pp. 79-87) and has also been discussed by Douglass (1919, p. 71). The sequoias used by Huntington (1914, pp. 160-162; fig. 42) in a comparison between tree-growth at Dillonwood and precipitation at Portersville, however, should be left out of this discussion, for there is hardly any agreement between the curves presented. Other factors than precipitation must

have essentially determined the growth of these trees. Regarding the trees at Hume, discussed by Huntington (1914, pp. 162-167), Douglass (1919, p. 71) remarks that the curves of growth may be given one year in error, and should be moved one year back. This, however, may not be the case, for the samples on which the measurements were made were cut about the middle of July, and of three of them, which Dr. Huntington and the writer have reexamined, two lack autumn wood entirely in the outermost ring.

The relationship between growth at Hume, lying 3 miles (5 km.) north-east of the General Grant National Park, and rainfall at Fresno-San Francisco is illustrated, after Huntington (1914, p. 163, fig. 44) and Douglass (1919, p. 71; fig. 21), in our figure 3. Fresno, which lies 50 miles (80 km.) from Hume and 70 miles (113 km.) from the south area for ring measurements of the big tree and at 5,000 to 6,000 feet (1,500 to 1,800 meters) lower elevation is the nearest station for meteorological data of sufficient length to be of any value. As Huntington (1914, pp. 157-159) pointed out, however, the proportional variation in rainfall from year to year in central California is very similar, even if the actual amount is very different. Curve *A* in figure 3 gives the precipitation at Fresno and before 1882 at San Francisco, reckoned from July to July. Curve *B*, as far back as 1884, is based upon 111 trees, and before that time upon 74 trees from Hume.

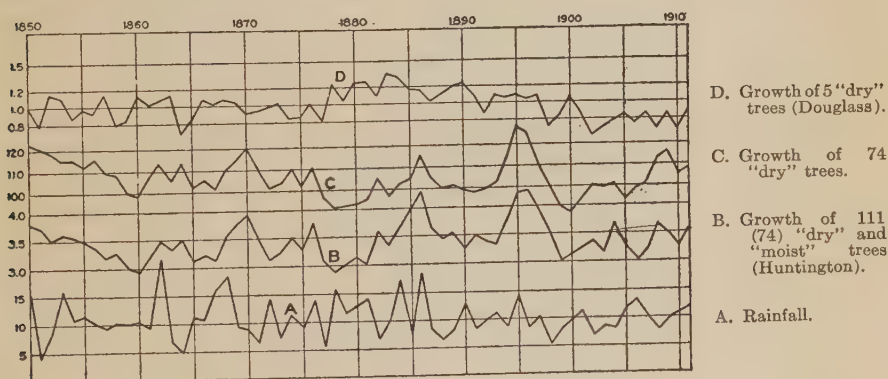


FIG. 3.—Growth of trees at Hume and rainfall at Fresno-San Francisco. (Huntington and Douglass.)

Huntington states that the trees were

"Scattered over an area of about a mile square. No fires appear to have occurred in the region for many years, certainly not during the last 30 or 40, and probably not for centuries. The trees were all strong and vigorous at the time when the sections were cut, and there was no sign that they were influenced by any special diseases or parasites. They were scattered in all sorts of locations, from places where swamps or perennial brooks bathed their roots to dry, rocky hillsides subject to constant drought."

The growth curve (*B*) bears some though not great similarity with the rainfall curve (*A*). If the curves were not dated, it would not be possible to connect them by means of agreement. The high parts and the low parts correspond sometimes, but in several instances maxima in the growth curve coincide with minima in the rainfall curve, and vice versa. The parts which agree best are the following: 1852 to 1859, 1861 to 1863, 1873 to

1877, 1885 to 1889, and 1899 to 1901. Reversed course of the curves occurs during the years 1863 to 1867, 1868 to 1870, 1871 to 1873, 1877 to 1879, 1880 to 1883, 1890 to 1894, 1895 to 1897, and 1901 to 1910.

Curve *C*, in figure 3, is based upon 74 measurements and largely upon trees used for curve *B* and exclusively on trees growing in dry situations at Hume. It is calculated from the growth totals of the trees belonging to groups IIA, III, and V (Huntington, 1914, p. 388). The curve agrees so well with curve *B* that practically all that has been said about the relation of this latter to the rainfall curve also has reference to the former. The differences are of no importance.

Curve *D* is taken from Douglass (1919, fig. 21, p. 71). It is based upon 5 sequoia trees at Hume. Douglass states (1919, p. 47) that the trees grew

"High up on a hillside, where the slope of the ground was 15° to 25° . It was not very far from the top of a sharp ridge and there was no opportunity for moisture to collect and remain for long periods on the soil. Therefore one would expect these trees to show variation related to the amount of snowfall each winter, if any did. The growth of some of these trees was large but full of constant variation, and they were therefore of the type which I have called 'sensitive.' They do in fact show best of any the relationship to precipitation."

Douglass finds that the growth curve shows "marked similarity in many details" with the Fresno rainfall curve. It follows the rainfall curve somewhat better than do the two other growth curves, but on the whole the correspondence is not good. The best agreement occurs during the years 1853 to 1856, 1875 to 1882, and 1893 to 1905. Were it not for the strongly increased growth during 1852, preceding the heavy precipitation of 1853, the correspondence would be good for the whole period 1850 to 1856. Fairly good agreement also exists from 1888 to 1892. From 1860 to 1870 there is some general correspondence, though there is disagreement in some details. Most noteworthy is the fact that the great precipitation in 1862, 1867, and 1868 is not associated with wide rings. During the period 1871 to 1874 there is no agreement or some reversed correspondence. During 1883 to 1887 hardly any agreement exists. The wide growth-ring of 1883 precedes the heavy rainfall of 1884, during which the growth falls a little.

As seen, curve *D* hardly shows any direct correspondence with curves *B* and *C*, which agree almost in detail with each other, in fact it is inverse to them during 1851 to 1853, 1856 to 1865, 1868 to 1875, 1877 to 1879, 1881 to 1886, 1887 to 1891, 1898 to 1902, etc. Since the trees upon which curves *C* and *D* are based have grown under the same conditions as far as temperature and precipitation are concerned, and under similar external conditions in other respects, the disagreement between the curves is very remarkable; so much more so as the agreement between the curves *B* and *C* is so great. The discrepancies may be due to differences in situation.

In Huntington's (1914, p. 166; 1922, pp. 79-82) mind conservation of moisture plays a great rôle. He states that sequoias growing on relatively dry slopes depend chiefly on the rainfall of the second and third preceding rainy seasons, and that trees growing in or close by water show the greatest correlation coefficient if the rainfall of 10 preceding years is taken into account. (See also Huntington, 1925.)

After-effect of rainy, favorable years over a few years on the long growth periods in a tree like the yellow pine growing in well-drained soil, as found

by Douglass (1919, pp. 66-71), seems plausible. Effects of the climatic conditions of the preceding season on the height growth of the same species, as discussed by Kirkwood (1914), is also natural; and as a general statement it can be said that the preceding season, or a few preceding seasons, are or can be of some importance, provided the soil is comparatively dry. The preceding rainy and favorable years may affect the growth less by conservation of moisture in the soil than by abundant accumulation of food reserves. However, MacDougal (1924, pp. 81-86) finds trees growing in well-drained soil to be much dependent on spring drought following upon winter precipitation, to respond with growth immediately upon rain, and to pause in enlargement during short periods of low relative humidity. Thus, it is not understood how the amount of snowfall during preceding winters could directly affect the growth of sequoias which grow in or close by perennial brooks and springs and in valley bottoms, which are swampy even during summers like 1912 (when Dr. Huntington made part of the ring measurements) after a precipitation in July 1911 to June 1912 much below the average (see McAdie, 1914, pp. 200, 214). It appears as if Huntington had assumed an unlikely relationship without proving its existence. Merely a little greater, but yet poor, agreement between the rainfall and growth curves, of course, does not prove the relationship in question. For instance, by assuming lag of some years a growth maximum is ascribed to a preceding rainfall maximum, while it in reality coincides with and perhaps is connected with a minimum of rainfall. Typical growth maxima under these conditions occur in curves *B* and *C*, figure 3, in 1864, 1869 to 1871, 1882, 1904, and 1908 to 1909. Similarly, growth minima coinciding with maxima in precipitation are ascribed to preceding rainfall minima.

The after-effects of the season may also be of other kinds. The growth of trees in comparatively dry sites can be checked during the year or years following a dry summer as a direct consequence of the drought, but growth is not bound to be so markedly affected unless the drought is so pronounced that the trees really suffer and fail to accumulate sufficient food reserves. On the other hand, trees with a good supply of ground water and favored during a dry and warm summer, on account of the great supply of reserves, might also be somewhat favored during the following summer. On the whole, however, the preceding years may not mean very much.

To sum up: The radial growth of the big tree shows some, though not great, direct relationship to the rainfall. In the case of trees living under dry conditions this correspondence can and may be direct. In the case of trees which, even during dry years, have abundant water-supply, there can not very well be a direct causal connection, for it seems highly improbable that trees in such situations can be directly favored or checked by a little smaller or heavier precipitation. The only exception may be that very heavy snowfall by shortening the growing season might check the growth. Satisfactory analysis of the conditions can not be made, since practically all data are lacking. The subordinate rôle of precipitation for the growth of the sequoia is also shown by other conditions, which will be discussed on pages 137 to 139. Here may be mentioned only that trees in dry sites react more slowly to the climatic factors governing the growth than do trees in moist situations.

TEMPERATURE.

Temperature is of great importance for the radial growth of trees. In moist climates, as in north Europe, temperature commonly is regarded as the dominating factor, both because the majority of trees have access to ground water and because heavy precipitation generally is connected with fall of temperature. Schwarz (1899, p. 131) says that the growth of the Scotch pine in Germany follows temperature much more than precipitation. The summer of 1901, which in Sweden was very warm and dry, greatly favored the radial growth of the pine, except in regions where the drought made itself particularly felt, while the rainy and chilly summer of 1902 checked it (Hesselman, 1904).

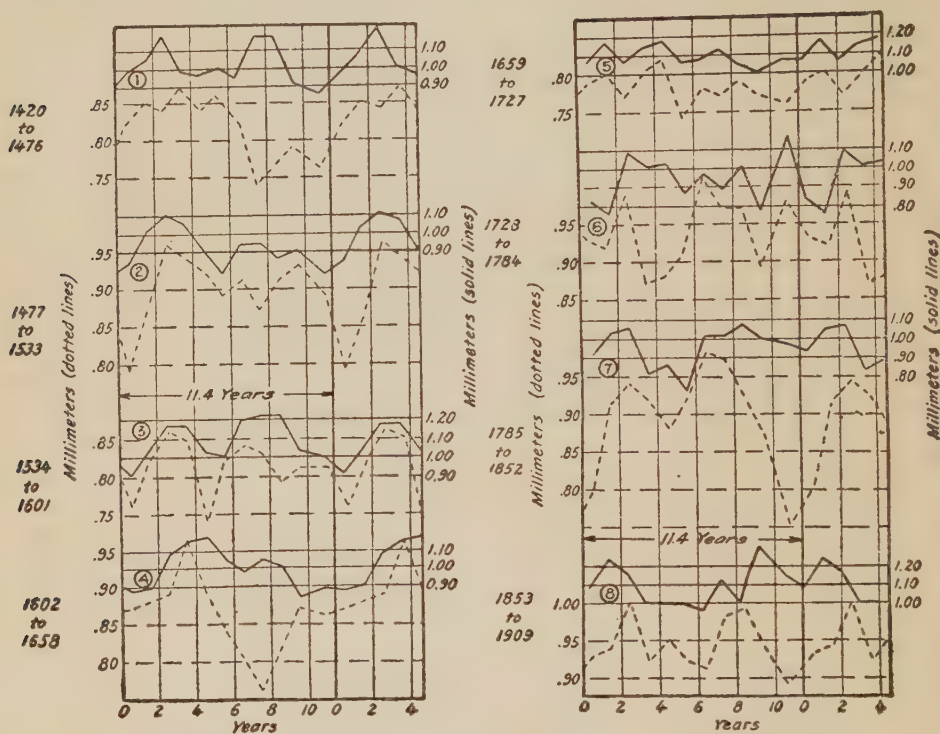


FIG. 4.—Changes in the 11-year period in 500 years. (Douglass.)

The effect of temperature on the growth of the big tree can only be estimated in a general way, since no meteorological data exist from the region where the species lives at elevations of from 5,000 to 7,000 feet (1,500 to 2,000 meters) and the temperatures there are very different from those down in the valleys and lowlands where meteorological records are gathered. The winters in the sequoia belt are intensely cold, with very heavy snowfall. The summers are mild and practically without precipitation. The temperature conditions, consequently, are much like those in cold temperate regions, and it therefore seems as if the summer temperatures should greatly influence the growth, particularly since at least 50 per cent of the sequoia trees live in swampy locations and seem to have more than the necessary water-supply.

Because of the thick layer of snow covering the ground at the end of the winter, high temperatures in spring may also play an important rôle by hastening the melting of the snow and other necessary processes preceding the time of growth. The thickness of the woody layer formed in any year in the Monterey pine, according to MacDougal (1924, pp. 9, 81), shows a general correlation to the length of the growing-season.

The temperatures during January to March, according to Schwarz (1899, pp. 106, 112), are more essential for the growth of the Scotch pine in Germany than are the temperatures in April to August.

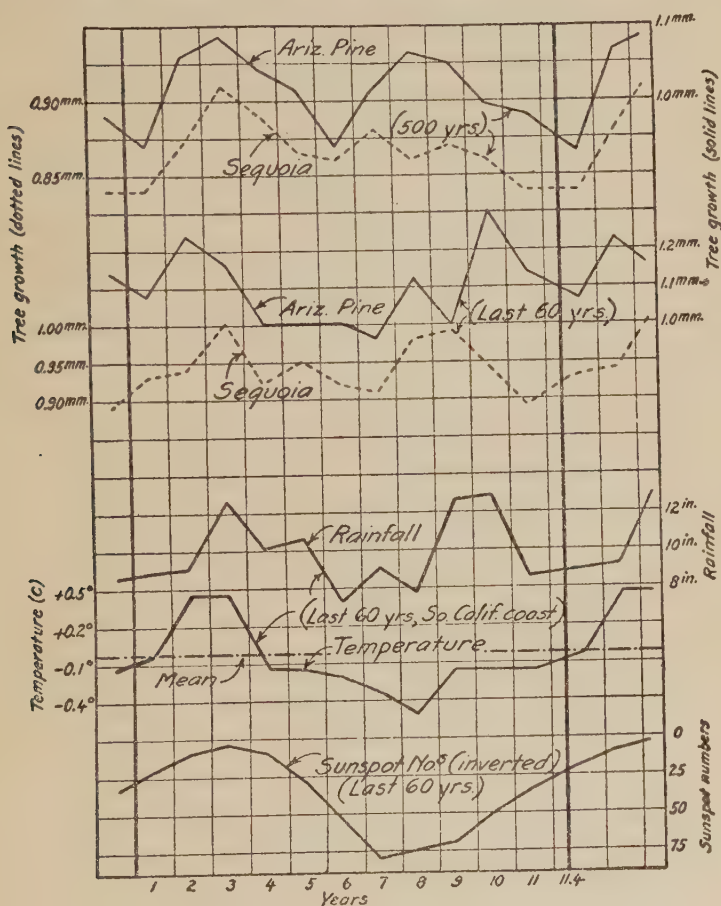


FIG. 5.—Correlation curves in the 11-year cycle. (Douglass.)

SUN RADIATION.

Trees living in the moist climate of north Europe and North America are by Douglass (1919, p. 65) found to vary in the rate of radial growth with the changes in solar activity so that the widest rings correspond to sunspot maxima. Douglass examined trees from Prussia, south Sweden, central Sweden, Christiania, the Norwegian west coast, south England, Vermont, etc. The growth of trees from all the European regions shows an unquestion-

able agreement with the sunspot curve; this is particularly the case in the growth of trees from the two first-mentioned regions. The trees from the inner coast of west Norway seem to show a reversed cycle. Trees from Pilsen in Bohemia and from the northern slopes of the Alps in Bavaria temporarily follow the variations of the sun. Hemlocks from Vermont examined show a certain, though not so good, correspondence with the sunspot curve if this is moved three years back after 1810; and before 1810 one year back. Since 1420 the giant redwood on the whole shows a fairly good rhythm in the sunspot cycle (Douglass, 1919, p. 102, figs 33, 34; our figs. 4 and 5). The double sunspot cycle is very regular.

The cause of the correspondence between tree growth and number of sunspots is not clear. In Scandinavia, according to Mielke (1913) and Köppen (1914), the temperature undergoes strong fluctuations without discernible relation to the sunspot curve. In north Germany and in Great Britain the temperature curves, which closely agree with each other, also show little or no agreement with the variations of the sunspots. In the Atlantic States of North America, on the other hand, the temperature, particularly since the end of the seventies, follows the changes of sunspots in a striking way. The surprising fact is, consequently, that the ring curve, on the whole, follows the sunspot curve most closely where the temperature curve is most independent of the sunspot curve, and vice versa. When a relationship exists among the three curves the greatest ring-width corresponds to the lowest temperature. This seems to indicate that tree-growth in temperate regions is less determined by temperature than has been commonly supposed. What rôle other well-known factors, such as precipitation and distribution of precipitation and temperature over the year, etc., play in each case, can not be said, since statements regarding them are mostly lacking. The growth of the pine trees in the vicinity of Berlin, however, also follows precipitation, since rainfall here is heaviest during sunspot maximum (König, 1914). The most favorable conditions for the pine in Germany, according to Schwarz (1899, pp. 106, 112, 129, 131), are high temperatures during the months January to March and abundant precipitation in May to July. The summer temperature comes secondarily, and the precipitation during the months preceding the vegetative period is without effect. On the whole, temperature means much more than does rainfall. Huntington (1914*a*, p. 496), calculating from Douglass's ring measurements on pine trees at Berlin and from the available meteorological data, the most favorable meteorological conditions for growth, came in detail to the same results, except that he put the rainfall first. The known facts, however, do not seem to explain satisfactorily the remarkable agreement between growth-curves and sunspot-curves, but probably tree-growth, in an essential degree, is determined by little-known factors in the sun's radiation, as rays of different physiologic effect.

The radiation of the sun, as Abbot, Fowle, and Aldrich (1913, pp. 130, 133; 1922, p. 206) have found, is strongest during sunspot maximum, and high values of the solar constant are attended by a greater increase of energy in the shorter wave-lengths than in the longer ones. In other words, during sunspot maximum particularly the blue parts of the sun spectrum are strengthened.

The effect of light upon the growth of plants is yet little known, and the statements are partly contradictory. Generally it seems to be deterrent

(Karsten, 1915; Meyer, 1920, p. 846; Illic, 1919). However, in all species studied by Garner and Allard (1920, p. 604) the rate of growth was directly proportional to the length of the daily exposure to light. Fries (1918, p. 17), who studied the influence of the arctic summer light on plants at Abisko ($68^{\circ} 20' N.$) in Swedish Lappland, found two distinct, biologic types of plants: one whose development is accelerated, and another whose development is checked. Red and yellow lights are generally most favorable (Schanz, see Meyer, 1920, p. 847), while green and blue rays are least favorable, and ultra-violet rays are injurious or even deadly (Flammarion; Ursprung and Blum, 1917; Meyer, 1920, p. 849).

METHODS OF CORRECTION.

The effects of the non-climatic factors mentioned above upon width of growth-rings evidently must be eliminated before the growth curves can record climatic conditions of the past.

The most essential thing for accurate results is selection of the material. This is also the most difficult task. For a study of the precipitation of the past, it is evidently necessary to select trees, the growth of which was determined primarily by the amount of rainfall—trees that felt the lack of rain during a dry year; for trees with good supply of ground water most probably form a wider ring during a dry year than during a rainy summer. Furthermore, only healthy, concentric and normally, uniformly, and in all respects well-developed trees, living under similar conditions, should be selected. Trees that have experienced casualties and considerable changes in the conditions of life caused by strong shading in youth, defoliation by fire, insects, or the like, should be avoided if possible. After plotting curves of the measured growth, further selection can be made.

Of fundamental weight is correct measurement and correct dating of the rings. If mistakes can not be avoided, correction should be applied for errors in counting, for missing rings and for double rings as done by Huntington (1914, pp. 144-150).

However carefully the selection be made, there always will remain individual variations of the growth curves depending on the different rates of growth at different ages, on reactions of the trees against external factors, etc. Most of the casual fluctuations can be fairly well eliminated by using a large number of trees distributed over a large area. The greater the number and the more widely distributed the trees, the more completely the undesirable effects are eliminated. In the case of the giant redwood, whose conditions of existence and history are comparatively little known, the number has proved to be most important. Generally the number of trees may be of less importance than careful selection.

For elimination of the different rates of growth of trees at young and old age, Huntington (1914, p. 123) worked out a mathematical method of correction. Here another method, correcting at the same time the different growths during the different stages of age and flaring in the old parts of the curves, will be described. This method has been proven to give practically the same result as does Huntington's.

According to this mode of correction, individual trees or groups of trees of the same age and showing similar curves of growth are corrected separately.

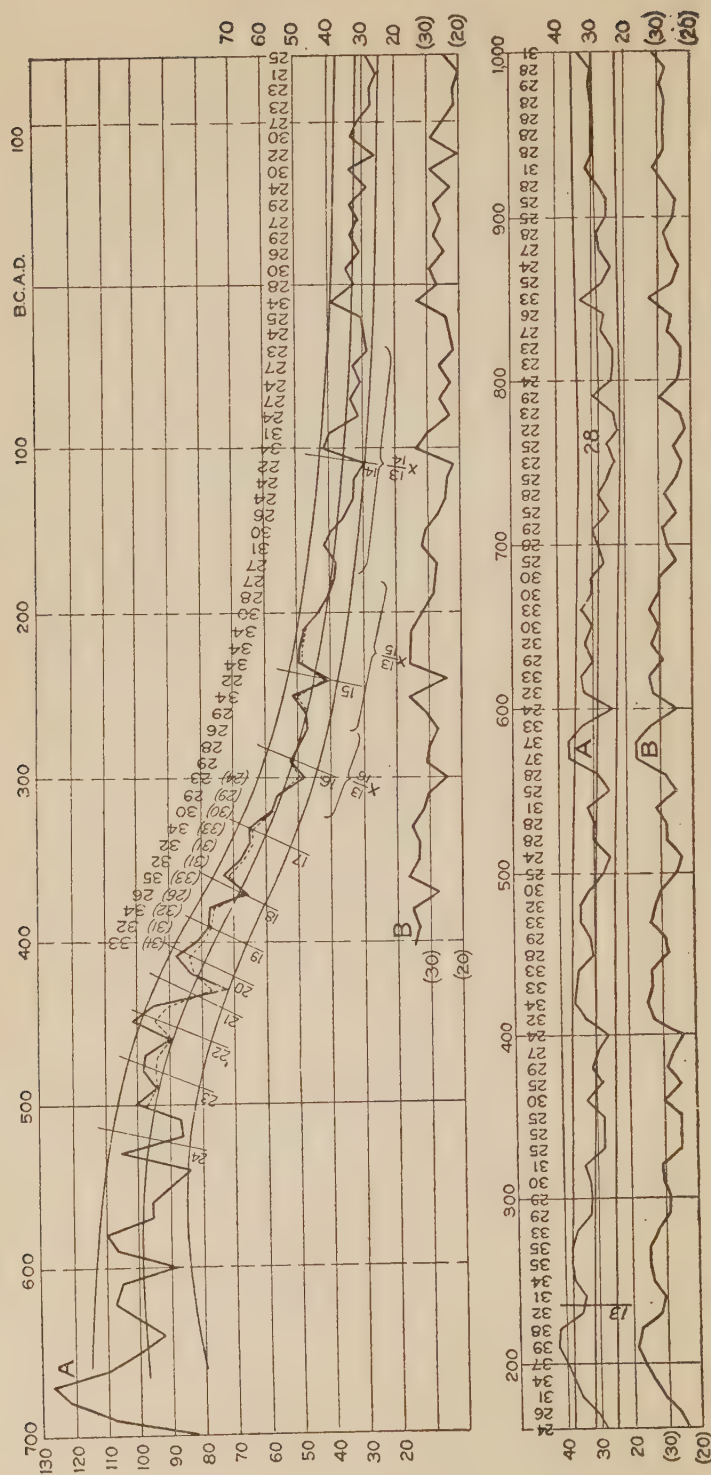


FIG. 6.—A, Curve illustrating method of correction; B, Curve A corrected. Curves broken. Only the essential parts are corrected. Scale $100^{\frac{1}{3}}$.

To this end, curves of the measured growth are plotted. Paper ruled with lines spaced 5 mm. has proved to be suitable. Figure 6, curve A, illustrates the method. It shows a curve representing the total growth of 5 trees of the same age. The curve represents Huntington's (1914, pp. 318-322) group 36, uncorrected growth. It has been broken and the parts from 860 to 700 B. C. and after 1,000 A. D. are omitted for the sake of space.

For correction, a middle or average line and tangents are drawn. In drawing the mid-line great care must be taken; comparison with curves of older groups will give valuable hints as to where the mid-line should run. The intention is to reduce the fluctuations of the curve from this mid-line to the same order and to straighten the mid-line. In this case the distance between the parallel parts of the tangents is 13 mm. In earlier years it is more than 25 mm. From a little below the point where the distance between the tangents is 14 mm. to halfway up, where it is 15 mm., the *perpendicular* distances of the points on the curve from this average line are multiplied by $\frac{1}{4}$; above this the distances are multiplied by $\frac{1}{3}$, $\frac{1}{6}$, etc., as shown in figure 6. The dashed line shows the resulting curve in which the fluctuations are reduced to the same order.

It now remains to reduce the whole curve to the same base; in other words, to straighten the average line. In this case the mid-line, where lowest—after 1000 A. D.—lies 28 mm. above the base. This line is followed by the 28-mm. line of a pocket rule, which is kept at *right angles* to the mid-line, and the points on the dashed curve and, below, on the unreduced curve are read off. The resultant figures are the corrected values. They are written above the curves, the reduced figures within parenthesis. In order to show the result, the curve of the unreduced figures is plotted in curve B. In practice, the final figures are calculated directly without plotting the dashed curve. This saves time and gives greater accuracy.

From the material obtained by correction of the different curves, a normal curve is calculated by taking the means of all. This curve evidently will be the more accurate the greater the material. If, as is generally the case, the fluctuations of the ring curves are very large in the earlier part of the curve and consequently difficult to correct, this part is omitted.

In practice it proved rather difficult to draw tangents and reduce the higher parts of the curves correctly. Furthermore, in most cases, the tangents run practically parallel, except in these earlier parts. Therefore, as a rule, though not always, only a mid-line has been drawn and the variations of the original curve from this mid-line simply read off, while the earlier portions of the curve have been omitted. In the example here taken (fig. 6), the part before 400 B. C. has been omitted and the unreduced values used.

Curves representing large numbers of measurements evidently are very high in the earlier parts and then fall rapidly. Since experience has shown that such rapidly rising curves can not be corrected with advantage, curves of such groups have been plotted in one-half or one-third natural scale, so that the rise has become gentle and as equal as possible in the different groups. After correction the resultant figures have been multiplied. This has proved to be a good method. Similarly, curves of groups consisting of a single or a few measurements have been plotted on enlarged scale.

Correction for flaring is provided by extending the average line through the whole of the curve, and reducing the curve to this line, just as when correcting for rapid growth during youth.

In the final curves, figure 7, curves 1 to 3 and curve 4 from 1000 B. C. to 1000 A. D., still another correction has been applied, namely, for changes caused by outgoing or incoming of groups whose average growth is greater or smaller than that of the other joint groups. To this end a curve is calculated, excluding the group in question, and the differences from the curve in which the group is included are figured out. The average amount of this difference is

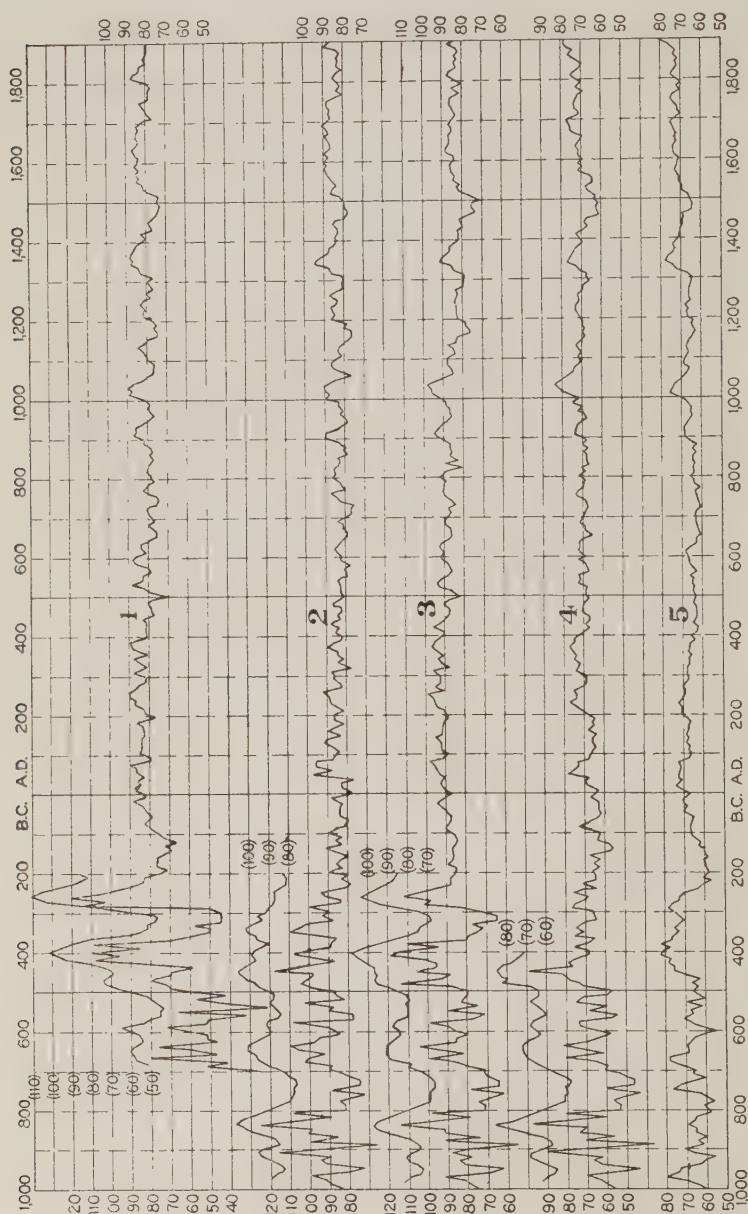


FIG. 7.—Climatic curves obtained from the big tree. 1, from trees in dry situations (Table 2, column d); 2, from trees in moist situations (Table 2, col. h); 3, from trees in dry and moist situations (Table 2, col. k); 4, from trees in all kinds of situations (Table 2, col. o); 5, Huntington's curve without the Caspian factor (Huntington, 1914, fig. 38, and Table C, p. 323, col. F).

added to or subtracted from those parts of the latter curve in which the outgoing or incoming curve is not represented. By the corrections applied, the secular climatic trend eventually recorded in the radial growth as a rule is lost; there does not seem to be any possibility to get hold of it. In order that the curve might express the probable desiccation during the last thousands of years, Huntington (1914, fig. 50, p. 172; pp. 174, 323) tilted his final curve, using the fluctuations of the level of the Caspian Sea as a measure. Here no attempt at tilting has been made.

From Huntington's material the trees living in dry and moist situations were selected and treated separately. Since it was supposed that the growth curves of the individual trees should show agreement, curves of the selected measurements were plotted in order to facilitate further selection. The curves, however, did not show good correspondence, so that selection could not be carried out as hoped, but they made it possible to discard those measurements or parts which were too individual and showed too marked differences from the majority.

The finally selected measurements belonging to the same age group—the division, used by Huntington, according to which group 1 comprises trees from 201 to 300 years old, group 2 trees from 301 to 400 years old, etc.—were added up (Table 1, p. 141). Curves were plotted from the totals. These curves were corrected for growth variations depending on age and flaring, as just described, so as to record the fluctuations of climate. The resultant figures were tabulated.

The parts of the curves between 1,301 and 2,100 years of age were added separately, and the parts younger than 1,301 years separately. Parts older than 2,100 years were not used. The sums obtained were divided by the number of measurements, and the results plotted in curves, which, however, are not published. By summing up the totals of the two groups and dividing by the sum of all measurements curves of the whole "dry" and the whole "wet" material were obtained (curves 1 and 2, fig. 7). These latter curves also were corrected for incoming and outgoing of groups with greater or less growth than the average, and record as accurately as the material permits the climatic fluctuations which have influenced the growth. Table 2, A and B, gives the summary of the elaborate tables.

From the whole dry and the whole moist material a curve was calculated by adding up the total corrected growth and dividing by the total number of measurements. Table 2c shows the figures, except the totals, and curve 3, figure 7, shows the curve.

Finally, another curve (curve 4, figure 7) was obtained in a somewhat different manner. From 1001 A. D. to 1900 A. D. it is based upon all Huntington's (1914, pp. 211–315) material belonging to the groups indicated in table 2D. Only the age stages from 1,301 to 2,100 years have been used and no correction whatever has been applied, except reduction to the horizontal plane of the straight average line which, in the uncorrected curve, rises because of flaring. The part from 1001 B. C. to 1000 A. D. is composed of all of Huntington's (1914, pp. 315–322) material belonging to the groups 20 to 31. It has been corrected by groups in the usual way. Only a summary of the tables is published.

GROWTH CURVES AND THEIR SIGNIFICANCE.

On the preceding pages has been shown how the varying rate of growth at different age-stages, effects of individual and local nature, flaring, etc., have been eliminated as accurately as possible from the growth curves. The remaining variations of the curves may be due largely to changes in climate and weather, though it must not be thought that every little fluctuation necessarily has climatologic significance. Importance should be attached only to large features.

As stated on this page, separate curves, not published, were calculated from measurements of those parts of trees that are less than 1,301 years old and from those parts that are 1,301 to 2,100 years old. The curves of parts under 1,301 years show fluctuations lacking in the other curves; besides, in these curves the maxima that also occur in the curves of parts 1,301 to 2,100 years old are more pronounced, commence earlier, and last longer.

"DRY" CURVE AND "MOIST" CURVE.

The finally corrected curves based upon all trees growing in dry and wet sites respectively (curves 1 and 2, figure 7) show better agreement with each other, the greater the material upon which they are based. Therefore the less exact correspondence in the earlier parts of the curves may in the first case be due to insufficient material. After 800 A. D. the correspondence is indeed remarkable. The curves are about equally pronounced. Marked maxima occur in both curves in the beginning of the tenth and eleventh centuries, during the fourteenth century, and from 1550 to 1750. A secondary maximum is common to both in the thirteenth century. Minima are common to both curves in the latter parts of the ninth, tenth, twelfth, thirteenth, fifteenth, and eighteenth centuries. The curves also show noteworthy differences, as the somewhat delayed appearance of the maxima in the dry curve, indicating slower reaction of the trees living in dry sites. Other differences are secondary maxima in the dry curve about 1130 and 1810 and in the wet curve 1080 to 1090, and 1890. Between 1 A. D. and 800 A. D. the curves do not show very good agreement, but present a great number of relatively small independent fluctuations. In common are a minimum during the third century, a secondary maximum about 370 and 380, as well as minima about 100, 500, 560 to 570, and 650 to 660.

The fluctuations in the earlier parts of the curves being very marked because of the scanty material, smoothed curves, calculated after the formula $\frac{a+2b+3c+2d+e}{9}$ and the resultant figure used for c , have been plotted above the actual growth curves. These smoothed curves show fairly good agreement from 700 to somewhat after 500 B. C., but after that they have rather independent courses. So have also the unsmoothed curves from 200 B. C. to 1 A. D.

ALL FINALLY CORRECTED CURVES.

A comparison of all finally corrected curves—that is, curves based upon trees in dry situations (curve 1, fig. 7), in moist situations (curve 2), in dry and moist situations (curve 3), in all kinds of situations (curve 4), and Huntington's (1914,

fig. 38, and table G, p. 323, column F) curve (without the Caspian factor; based upon trees in all kinds of situations and obtained after a different method of correction (curve 5)—reveals the remarkable fact that they all agree in those parts that are computed from a very large quantity of material. Thus, the correspondence is particularly good, partly even detailed, since 800 A. D. All of the curves show maxima in the beginning of the tenth and eleventh centuries, during the fourteenth century, and since about 1550. They have minima in the latter parts of the tenth and twelfth centuries and about 1300 and 1500. During the eighteenth century the dry curve (curve 1) falls lower than the rest, and from 1770 to 1880 the wet curve (curve 2) is rather low. Since 1850 the dry curve remains low, while curves 2, 4, and 5 rise.

This writer has not extended the curves beyond 1000 B. C., since only a few trees reach farther back and elimination of the factors of non-climatic nature therefore hardly can be made. The smoothed curves (curves 2, 3, and 4), from 1000 to 700 B. C., where largely computed from the same material, show good agreement with each other, but hardly any correspondence to Huntington's curve (curve 5), which has partly reversed course. From 700 to 500 B. C. all curves, including that of Huntington, agree rather well. Between 500 and 200 B. C., as mentioned, the maxima and minima in trees living in dry and moist situations occur at different times, giving all the curves different courses. Huntington's curve follows our curve 3 most closely. Not too much weight should be laid upon these earlier parts, for the material is too small for elimination of non-climatic features, and satisfactory correction of them can not be made. To get around this last-mentioned difficulty, this writer has excluded the earliest parts of the trees, and this fact probably is the reason for some of the discrepancies between the writer's curves and that calculated by Huntington.

From about 200 B. C. to 800 A. D. all the curves present a great number of small fluctuations, and show neither marked similarities nor discrepancies. From 200 to 100 B. C., curves 1 and 5, however, are considerably low; and from 150 to 130 B. C. curve 4 also is very low.

The agreement between those parts of the curves that are calculated from a very large quantity of material is particularly significant, since different methods of correction and different age-stages of the trees have been used to construct them. The agreements, consequently, are real, of external origin and almost certainly of climatic nature. This fact, together with conditions set forth on pages 125 to 132, signifies that the growth of the big tree, allowance made for eccentricity, effects of casualties, etc., is essentially determined by a combination of factors, and that the rôle played by each factor is subordinate and varying. The dependence of tree growth on the entire constellation of environmental conditions, not on individual conditions, is also emphasized by MacDougal (1924, p. 81) and Shreve (1924, p. 116).

The chief climatic factors influencing tree-growth, as discussed on pages 125 to 132, appear to be precipitation, temperature, and sun radiation. The relative rôle of each factor is dependent on the time of its influence, upon other factors, upon internal conditions in the tree, upon earlier conditions in general, etc. Thus, growth can primarily follow now this, now that, factor. No direct study of the relationship has ever been made, so that not even the general laws are known. In the case of the big tree the importance of the

individual factors is much more difficult to estimate, as data of temperature are entirely wanting. However, it appears to be certain that the sequoia curves do not specially record precipitation. High parts in the curves might directly or indirectly be connected with periods of heavy rainfall and low parts with scanty rainfall, because of the relationship between the different climatic factors as influenced by the activity of the sun, so that trees in moist and dry sites might be favored or checked contemporaneously by different factors, but it can not be concluded that all high and low parts were connected with rainfall and drought. In this connection it is noteworthy that the tree-growth maximum during the fourteenth century coincides with an exceptional spottedness of the sun (Huntington and Visser, 1922, p. 109) and with the climatic stress, of which there are abundant historical records in the Old World, and which particularly expressed itself in unusually cold winters, cold rainy summers, and devastating storms.

Accordingly, before satisfactory interpretation of the sequoia curves and conclusions from them regarding the climate of the past can be made, it is necessary to have data on temperature, better knowledge of the relation between precipitation and growth of sequoia trees in dry situations, and general knowledge of the rôle for growth played by the radiation of the sun.

Besides being of climatological interest, the sequoia curve is of importance as eventually affording a possibility to extend the Swedish postglacial geochronology up to the present time. This chronology (not yet published), worked out by Ragnar Lidén (1911) in the valley of the River Ångermanälven (63° N.), is based upon annually laminated silty clays deposited in fiords of the Gulf of Bothnia ever since the disappearance of the last ice-sheet. The annual deposit consists of two thin layers, in texture and in color somewhat different, one of which may be essentially deposited in connection with the flood of the rivers during the melting of the snow in spring. By the upheaval of land, amounting to about 920 feet (280 meters), the clays have been gradually raised above sea-level and trenched by the rivers. Those from the last hundreds of years are not yet accessible, and Lidén has had to estimate the length of time that has elapsed since the formation of the youngest measured varve or annual layer.

This gap in the record might be bridged by help of the sequoia curve, for it seems likely that it will show a certain correspondence to the sedimentation curve in Norrland. The climatic stress during the fourteenth century, so distinctly recorded in the sequoia curve, is probably also recorded in the clay deposition. If this prove to be the case, and also other marked fluctuations in the tree curve are found in the clay curve, a connection may be made with high degree of probability, and the length of the postglacial time, which amounts to 8,500 to 9,000 years, exactly determined.

TABLE 2.—*Summary of growth of the Big Tree.*(See p. 137 and fig. 7).¹

Columns *c*, *g*, and *j*, and column *n* from 1000 B. C. to 1000 A. D., give average growth corrected for flaring and for different growth during the different stages of age.

Columns *d*, *h*, and *k*, and column *o* from 1000 B. C. to 1000 A. D., give average growth further corrected for changes caused by outgoing or incoming of groups whose average growth is greater or smaller than that of the joint other groups.

Column *n*, after 1000 A. D., gives average uncorrected growth.

Column *o*, after 1000 A. D., gives average growth corrected for flaring only; only those parts of trees are used that are between 1,300 and 2,100 years old.

Date of decade.	A. Trees in dry situations (Table 1A).				B. Trees in moist situations (Table 1B).				C. Trees in dry and moist situations (Tables 1A, 1B).			D. Trees in all kinds of situations; all trees belonging to Huntington (1914, pp. 311-322) groups.		
	<i>a</i>	<i>b</i>	<i>c</i>	<i>d</i>	<i>e</i>	<i>f</i>	<i>g</i>	<i>h</i>	<i>i</i>	<i>j</i>	<i>k</i>	<i>l</i>	<i>m</i>	<i>n</i>
	Groups.	No. of measurements.	Curve 1		Groups.	No. of measurements.	Curve 2		No. of measurements.	Curve 3		Groups.	No. of measurements.	Average growth.
			Average growth.				Average growth.			Average growth.				
A. D.														
1891-1900	8 to 20	130	8.0		8 to 20	131	8.6		261	8.3	8.4	12 to 19	259	9.1
1881-90		160	8.0			177	9.1		337	8.6	8.7		328	9.2
1871-80		165	8.0			186	8.4		351	8.2	8.3		341	9.0
1861-70			8.0			187	8.2		352	8.1	8.2			8.6
1851-60			8.1				8.4			8.3	8.4			8.9
1841-50			8.0				8.3			8.2	8.3	12 to 19	341	8.5
1831-40			8.3				8.4			8.3	8.4	13 to 20	331	8.2
1821-30			8.3				8.1			8.2	8.3			8.2
1811-20			8.6				8.4			8.5	8.6			8.5
1801-10		165	8.7				8.6		352	8.6	8.7	13 to 20	331	8.7
1791-1800		169	8.0				8.4		356	8.4	8.5	13 to 21	348	8.4
1781-90			7.8				8.2			8.0	8.1	13 to 21	348	8.2
1771-80			7.9				8.4			8.5	8.6	14 to 21	299	8.3
1761-70			7.9				8.1			8.1	8.2			7.9
1751-60	8 to 20	169	7.9		8 to 20	187	8.6		356	8.4	8.5			8.2
1741-50	8 to 21	177	8.3		8 to 21	194	8.9		371	8.6	8.7			8.4
1731-40			8.7				8.9			8.6	8.7			8.4
1721-30			8.1				8.8			8.5	8.6			8.3
1711-20			8.0				8.8			8.4	8.5			8.1
1701-10		177	7.7			194	8.7		371	8.3	8.4			8.1
1691-1700		181	8.2			197	8.9		378	8.7	8.6			8.6
1681-90			8.5				9.1			8.8	8.7			8.6
1671-80			8.4				8.9			8.7	8.6			8.5
1661-70			8.5				8.8			8.7	8.6	14 to 21	299	8.5
1651-60	8 to 21	181	8.5		8 to 21	197	8.9		378	8.8	8.7	15 to 22	272	8.0
1641-50	8 to 22	193	8.3	8.4	8 to 22	207	8.8		400	8.6	8.7			8.0
1631-40			8.4	8.5			8.7			8.6	8.7			8.1
1621-30			8.7	8.8			8.7			8.7	8.8			8.2
1611-20			8.6	8.7		207	9.0		400	8.8	8.9			8.1
1601-10		193	8.3	8.4		209	8.8		402	8.6	8.5			8.0

¹ Tables showing uncorrected and corrected growth by groups for each decade, etc., have been prepared; but being very elaborate they are not published. They can be consulted at the Carnegie Institution of Washington.

TABLE 2.—*Summary of growth of the Big Tree—Continued.*

Date of decade.	A. Trees in dry situations (Table 1A).				B. Trees in moist situations (Table 1B).				C. Trees in dry and moist situations (Tables 1A, 1B).			D. Trees in all kinds of situations; all trees belonging to Huntington's (1914, pp. 311-322) groups.			
	Groups.	No. of measurements.	c	d	Groups.	No. of measurements.	g	h	No. of measurements.	j	k	Groups.	No. of measurements.	n	o
				Curve 1				Curve 2			Curve 3				Curve 4
			Average growth.	Average growth.			Average growth.	Average growth.							
591-1600	8 to 22	198	8.3	8.4	8 to 22	209	9.0		407	8.6	8.5	15 to 22	272	7.9	7.0
581-90			8.6	8.7			8.9			8.7	8.6	15 to 22	272	8.1	7.2
571-80			8.3	8.4			9.0			8.7	8.6	15 to 23	283	7.9	7.0
561-70			8.5	8.6			8.9			8.7	8.6	15 to 23	283	8.1	7.2
551-60	8 to 22	198	8.3	8.4	8 to 22	209	8.8		407	8.5	8.4	16 to 23	236	7.4	6.6
541-50	8 to 23	200	8.4	8.5	8 to 23	213	8.6		413					7.4	6.6
531-40			8.1	8.2			8.4				8.5			7.4	6.6
521-30			8.0	8.1			8.6				8.3			7.6	6.8
511-20			7.8	7.9			8.7				8.2			7.4	6.7
501-10			7.3	7.4	8 to 23	213	8.2		413		7.7			7.0	6.3
491-1500			7.4	7.5	8, 10-23	200	8.0		400		7.1			7.1	6.4
481-90			7.2	7.3			8.0				7.6			6.9	6.3
471-80			7.3	7.4			8.0				7.6	16 to 23	236	6.9	6.3
461-70			7.4	7.5			7.9				7.4	17 to 24	205	6.9	6.3
451-60			7.6	7.7	8, 10-23	200	8.0		400		7.8			6.9	6.3
441-50			7.8	7.9	8, 10-24	202	8.5		402		8.2			7.5	6.9
431-40			7.7	7.8			8.6				8.1			7.6	7.0
421-30			7.6	7.7			8.4				8.0			7.4	6.8
411-20			8.2	8.3			8.4				8.3			7.6	7.0
401-10			7.9	8.0			8.5				8.2	17 to 24	205	7.8	7.2
391-1400			8.2	8.3			8.4				8.2	17 to 25	209	7.7	7.1
381-90			8.4	8.5			8.5				8.5			7.6	7.0
371-80			8.5	8.6			8.8				8.7	17 to 25	209	7.8	7.2
361-70			8.6	8.7			8.8				8.7	18 to 25	162	8.0	7.4
351-60	8 to 23	200	8.7	8.8			9.1		402		8.9			8.0	7.5
341-50	8 to 23, 25	206	8.6	8.7			9.4		408		9.0			8.1	7.6
331-40			8.7	8.8			9.5				9.1			8.2	7.7
321-30			8.3	8.4			8.8				8.6			7.8	7.3
311-20			8.2	8.3			8.7				8.5			7.6	7.1
301-10			7.6	7.7			8.2				8.0			7.3	6.8
291-1300			7.9	8.0			8.1				8.0			7.3	6.8
281-90			7.7	7.8			8.2				8.0			7.2	6.7
271-80			7.6	7.7			8.1				8.0	18 to 25	162	7.4	7.0
261-70			8.0	8.1			8.5				8.4	19 to 25	132	7.4	7.0
251-60			7.7	7.8			8.8				8.3	19 to 25	132	7.6	7.2
241-50			8.1	8.2			8.4				8.3	19 to 26	137	7.6	7.2
231-40			8.3	8.4			8.5				8.4			7.6	7.2
221-30			8.0	8.1			8.7				8.3			7.7	7.3
211-20			8.1	8.2			8.6				8.3			7.6	7.3
201-10	8-23, 25	206	8.1	8.2	8, 10-24	202	8.6		408		8.3			7.5	7.2
191-1200	10-23, 25	193	7.6	7.7	8, 10, 12-24	188	8.7		381	8.2	8.3			7.4	7.1
181-90			7.4	7.5	26		7.9			7.8	7.9			7.4	7.1
171-80			7.6	7.7			8.1			7.8	7.9			7.3	7.0
161-70			7.4	7.5			7.7			7.6	7.7			7.2	6.9
151-60	10-23, 25	193	7.4	7.5			7.7		381	7.6	7.7	19 to 26	137	7.3	7.1
141-50	10-23, 25, 27	195	7.9	8.0			7.9		383	8.2	8.3	20 to 27	114	7.2	7.0

TABLE 2.—*Summary of growth of the Big Tree—Continued.*

Date of decade.	A. Trees in dry situations (Table 1A).				B. Trees in moist situations (Table 1B).				C. Trees in dry and moist situations (Tables 1A, 1B).			D. Trees in all kinds of situations; all trees belonging to Huntington's (1914, pp. 311-322) groups.							
	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o				
																Curve 1	Curve 2	Curve 3	Curve 4
Groups.	No. of measurements.	No. of measurements.	No. of measurements.	No. of measurements.	No. of measurements.	No. of measurements.	No. of measurements.	No. of measurements.	No. of measurements.	No. of measurements.	No. of measurements.	No. of measurements.	No. of measurements.	No. of measurements.	No. of measurements.				
1131-40	10-23, 25, 27	195	8.1	8.2	8, 10, 12-24, 26	188	8.0		383	8.3	8.4	20 to 27	114	7.4	7.5				
1121-30			8.4	8.5			8.3			8.7	8.8			7.5	7.6				
1111-20			8.1	8.2			8.4			8.4	8.5			7.5	7.6				
1101-10			8.0	8.1	8, 10, 12-24, 26	188	8.2		383	8.3	8.4			7.3	7.4				
1091-1100			7.9	8.0	10, 12-24, 26	181	8.5		376	8.4	8.8			7.4	7.5				
1081-90			7.6	7.7			8.7			8.4	8.8			7.2	7.3				
1071-80			7.6	7.7			8.7			8.4	8.8			7.4	7.5				
1061-70			7.6	7.7			8.3			8.2	8.6			7.6	7.7				
1051-60			8.0	8.1			7.7			8.1	8.5			7.7	7.8				
1041-50			8.1	8.2			8.3			8.5	8.9	20 to 27	114	7.9	7.8				
1031-40			8.6	8.7			8.8			9.0	9.4	20 to 29	115	8.2	8.1				
1021-30			8.9	9.0			9.1			9.4	9.8			8.4	8.3				
1011-20			8.7	8.8			9.0			9.2	9.6			8.1	8.0				
1001-10	10-23, 25, 27	195	8.8	8.9			8.9		376	9.2	9.6	20 to 29	115	7.9	7.8				
991-1000	11-23, 25, 27	178	8.1	8.3			9.0		359	8.5	9.3	20 to 31	118		7.2				
981-90			7.7	7.9			8.3			8.1	8.9				7.5				
971-80			7.8	8.0			8.3			8.1	8.9				7.0				
961-70			7.7	7.9			8.1			7.9	8.7				7.2				
951-60			7.5	7.7			8.3			7.9	8.7				7.0				
941-50			7.7	7.9			8.0			7.8	8.6				6.9				
931-40			8.1	8.3			7.9			8.0	8.8				7.0				
921-30			8.4	8.6			8.2			8.3	9.1				7.3				
911-20			8.4	8.6			8.6			8.5	9.3				7.4				
901-10	11-23, 25, 27	178	8.5	8.7	10, 12-24, 26	181	9.0		359	8.7	9.5				7.4				
891-900	13-23, 25, 27	134	7.7	8.2	12-24, 26	172	8.8	9.0	306	8.3	9.3				7.1				
881-90			7.7	8.2			8.2	8.4		8.0	9.0				6.9				
871-80			7.4	7.9			7.9	8.1		7.7	8.7				7.1				
861-70			7.3	7.8			7.9	8.1		7.7	8.7				6.8				
851-60			7.4	7.9	12-24, 26	172	7.7	7.9	306	7.6	8.6				7.0				
841-50			7.2	7.7	12-24, 26, 30	173	8.2	8.4	307	7.7	8.7				6.9				
831-40			7.4	7.9			8.1	8.3		7.3	8.3				6.9				
821-30			7.5	8.0			8.2	8.4		7.9	8.9				6.8				
811-20			7.6	8.1			8.4	8.6		8.1	9.1				7.1				
801-10			7.4	7.9	12-24, 26, 30	173	8.2	8.5	307	7.9	8.9				7.0				
791-800			7.4	7.9	13-24, 26, 30, 31	161	8.3	8.7	295	8.1	9.1				7.2				
781-90			7.2	7.7			8.0	8.4		7.9	8.9				7.0				
771-80			7.5	8.0			7.8	8.2		8.0	9.0				7.0				
761-70			7.8	8.3			7.7	8.1		8.0	9.0				7.1				
751-60			7.6	8.1			8.4	8.8		8.1	9.1				7.3				

TABLE 2.—*Summary of growth of the Big Tree—Continued.*

Date of decade.	A. Trees in dry situations (Table 1A).				B. Trees in moist situations (Table 1B).				C. Trees in dry and moist situations (Tables 1A, 1B).			D. Trees in all kinds of situations; all trees belonging to Huntington's (1914, pp. 311-322) groups.											
	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o								
																No. of measurements.	Curve 1	No. of measurements.	Curve 2	No. of measurements.	Curve 3	No. of measurements.	Curve 4
Groups.	Groups.	Groups.	Groups.	Groups.	Groups.	Groups.	Groups.	Groups.	Groups.	Groups.	Groups.	Groups.	Groups.	Groups.	Groups.								
1841-50	13-23, 25, 27	134	7.1	7.6	13-24, 26, 30, 31	161	8.1	8.5	295	8.0	9.0	20 to 31	118		7.4								
1831-40			7.0	7.5	.....	.....	7.9	8.3	.....	7.7	8.7	.....	.....	.....	6.9								
1821-30			7.1	7.6	.....	.....	7.2	7.6	.....	7.4	8.5	.....	.....	.....	6.9								
1811-20			7.6	8.1	.....	.....	7.4	7.8	.....	7.8	8.8	.....	.....	.....	6.8								
1801-10			7.5	8.0	.....	.....	7.4	7.8	.....	7.7	8.7	.....	.....	.....	6.9								
1891-700			7.4	7.9	.....	.....	7.6	8.0	.....	7.9	8.9	.....	.....	.....	7.0								
1881-90			7.2	7.7	.....	.....	8.1	8.5	.....	8.0	9.0	.....	.....	.....	7.1								
1871-80			7.5	8.0	.....	.....	7.8	8.2	.....	8.0	9.0	.....	.....	.....	7.2								
1861-70			7.3	7.8	.....	.....	7.8	8.2	.....	7.8	8.8	.....	.....	.....	6.9								
1851-60			7.1	7.6	.....	.....	7.6	8.0	.....	7.7	8.8	.....	.....	.....	6.9								
1841-50			7.1	7.6	.....	.....	7.6	8.0	.....	7.7	8.7	.....	.....	.....	6.6								
1831-40			7.4	7.9	.....	.....	7.8	8.2	.....	7.9	8.9	.....	.....	.....	7.1								
1821-30			7.9	8.4	.....	.....	8.0	8.4	.....	8.2	9.2	.....	.....	.....	7.3								
1811-20			7.9	8.4	.....	.....	8.2	8.6	.....	8.3	9.3	.....	.....	.....	7.2								
1801-10	13-23, 25, 27	134	7.6	8.1	13-24, 26, 30, 31	161	8.1	8.5	295	8.1	9.1	.....	.....	.....	7.3								
1891-600	13, 16-23, 25, 27	113	7.8	8.6	13, 16-24, 26, 30, 31	112	7.2	8.3	225	7.5	9.2	.....	.....	.....	6.9								
1881-90			8.0	8.8	.....	.....	7.2	8.3	.....	7.5	9.2	.....	.....	.....	7.3								
1871-80			7.7	8.5	.....	.....	6.7	7.8	.....	7.2	8.9	.....	.....	.....	7.0								
1861-70			7.2	8.0	.....	.....	7.0	8.1	.....	7.1	8.8	.....	.....	.....	6.9								
1851-60	13, 16-23, 25, 27	113	7.1	7.9	13, 16-24, 26, 30, 31	112	6.9	8.0	225	7.0	8.7	.....	.....	.....	6.8								
1841-50	13, 17-23, 25, 27	106	7.4	8.3	16-24, 26, 30, 31	95	6.9	8.0	201	7.2	8.9	.....	.....	.....	7.3								
1831-40			7.4	8.3	.....	.....	7.4	8.5	.....	7.5	9.2	.....	.....	.....	7.2								
1821-30			8.0	8.9	.....	.....	7.3	8.4	.....	7.7	9.4	.....	.....	.....	7.4								
1811-20			7.4	8.3	.....	.....	7.7	8.8	.....	7.6	9.3	.....	.....	.....	6.9								
1801-10	13, 17-23, 25, 27	106	7.0	7.9	.....	.....	7.2	8.3	201	7.0	8.7	.....	.....	.....	6.9								
1891-500	17-23, 25, 27	87	6.0	7.1	.....	.....	7.1	8.2	182	6.5	8.3	.....	.....	.....	6.9								
1881-90			6.7	7.8	.....	.....	7.4	8.5	.....	7.0	8.8	.....	.....	.....	6.8								
1871-80			7.0	8.1	.....	.....	7.6	8.7	.....	7.3	9.1	.....	.....	.....	7.0								
1861-70			6.8	7.9	.....	.....	7.2	8.3	.....	7.0	8.8	.....	.....	.....	7.1								
1851-60			6.8	7.9	.....	.....	7.2	8.3	.....	7.0	8.8	.....	.....	.....	7.1								
1841-50			6.7	7.8	.....	.....	7.4	8.5	.....	7.1	8.9	.....	.....	.....	6.8								
1831-40			7.2	8.3	.....	.....	7.3	8.4	.....	7.3	9.1	.....	.....	.....	6.8								
1821-30			7.1	8.2	.....	.....	7.7	8.8	.....	7.5	9.3	.....	.....	.....	7.0								
1811-20			7.1	8.2	.....	.....	7.3	8.4	.....	7.8	9.6	.....	.....	.....	6.8								
1801-10			7.1	8.2	16-24, 26, 30, 31	95	7.5	8.6	182	7.3	9.1	.....	.....	.....	7.1								
1891-400			7.1	8.2	16-18, 20-24, 26, 30, 31	88	7.1	8.2	175	7.2	9.1	.....	.....	.....	7.3								
1881-90			7.7	8.8	.....	.....	7.2	8.3	.....	7.5	9.4	.....	.....	.....	7.5								
1871-80			7.9	9.0	.....	.....	7.6	8.7	.....	7.7	9.6	.....	.....	.....	7.5								

TABLE 2.—*Summary of growth of the Big Tree—Continued.*

Date of decade.	A. Trees in dry situations (Table 1A).				B. Trees in moist situations (Table 1B).				C. Trees in dry and moist situations (Tables 1A, 1B).			D. Trees in all kinds of situations; all trees belonging to Huntington (1914, pp. 311-322) groups.							
	Groups.	No. of measurements.	c	d	Groups.	No. of measurements.	g	h	No. of measurements.	j	k	Groups.	No. of measurements.	n	o				
																Curve 1		Curve 2		Curve 3		Curve 4
			Average growth.				Average growth.			Average growth.				Average growth.					
361-70	17-23, 25, 27	87	7.7		8.8	16-18, 20-24, 26, 30, 31	88		7.9	9.0		175	7.8	9.7		20, to 31	118	7.7	8.8
351-60			7.6	8.7	.....	.....	7.4	8.5	.....	7.5	9.4	.....	.....	7.6	8.7				
341-50			7.0	8.1	.....	.....	7.4	8.5	.....	7.2	9.1	.....	.....	7.4	8.5				
331-40			7.7	8.8	.....	.....	7.1	8.2	.....	7.5	9.4	.....	.....	7.5	8.8				
321-30			7.4	8.5	.....	.....	7.4	8.5	.....	7.3	9.2	.....	.....	7.2	8.5				
311-20			7.1	8.2	.....	.....	6.7	7.8	.....	6.9	8.8	.....	.....	7.3	8.2				
301-10	17-23, 25, 27	87	7.7	8.8	16-18, 20-24, 26, 30, 31	88	7.7	8.8	175	7.7	9.6	.....	.....	7.4	8.8				
291-300	18-23, 25, 27	64	6.7	8.9	17, 18, 20-24, 26, 30, 31	79	7.6	8.7	143	7.2	9.3	.....	.....	6.9	8.9				
281-90			6.7	8.2	.....	.....	7.6	8.7	.....	7.2	9.3	.....	.....	6.9	8.2				
271-80			7.0	8.5	.....	.....	7.3	8.4	.....	7.2	9.3	.....	.....	6.9	8.5				
261-70			7.2	8.7	.....	.....	7.6	8.3	.....	7.4	9.5	.....	.....	7.1	8.7				
251-60			7.6	9.1	.....	.....	8.1	9.3	.....	7.9	9.0	.....	.....	7.5	9.1				
241-50			7.6	9.1	.....	.....	8.0	9.0	.....	7.8	9.9	.....	.....	7.4	9.1				
231-40			7.2	8.7	.....	.....	7.8	8.9	.....	7.5	9.6	.....	.....	7.4	8.7				
221-30			7.3	8.8	.....	.....	7.8	8.9	.....	7.5	9.6	.....	.....	7.7	8.8				
211-20			6.9	8.4	.....	.....	7.6	8.7	.....	7.3	9.4	.....	.....	7.4	8.4				
201-10			6.8	8.3	17, 18, 20-24, 26, 30, 31	79	7.1	8.2	143	7.0	9.1	20 to 31	118	7.0	8.3				
191-200			6.3	7.8	18, 20-24, 26, 30, 31	58	7.6	8.7	122	6.9	9.0	21 to 31	69	6.5	7.8				
181-90			6.2	7.7	.....	.....	7.6	8.7	.....	6.8	8.9	.....	.....	6.2	7.7				
171-80			6.9	8.4	.....	.....	7.1	8.2	.....	7.0	9.1	.....	.....	6.3	8.4				
161-70			6.8	8.3	.....	.....	7.5	8.6	.....	7.1	9.2	.....	.....	6.2	8.3				
151-60			6.8	8.3	.....	.....	7.9	9.0	.....	7.1	9.2	.....	.....	6.5	8.3				
141-50			6.9	8.4	.....	.....	7.3	8.4	.....	7.1	9.2	.....	.....	6.1	8.4				
131-40			6.9	8.4	18, 20-24, 26, 30, 31	58	7.9	9.0	122	7.4	9.5	.....	.....	6.3	8.4				
121-30			6.9	8.4	20-24, 26, 30, 31	42	7.7	9.1	106	7.2	9.3	.....	.....	6.3	8.4				
111-20			7.0	8.5	.....	.....	7.3	8.7	.....	7.1	9.2	.....	.....	6.2	8.5				
101-10	18-23, 25, 27	64	7.1	8.6	20-24, 26, 30, 31	42	7.0	8.4	106	7.1	9.2	.....	.....	6.3	8.6				
91-100	18, 20-23, 25, 27	52	6.2	8.0	21-24, 26, 30, 31	28	6.9	8.6	80	6.4	8.8	.....	.....	6.4	8.0				
81-90			6.3	8.1	.....	.....	7.0	8.7	.....	6.7	9.1	.....	.....	6.5	8.1				
71-80			7.3	9.1	.....	.....	7.9	9.6	.....	7.4	9.8	.....	.....	7.1	9.1				
61-70			6.9	8.7	.....	.....	7.9	9.6	.....	7.2	9.6	.....	.....	7.0	8.7				
51-60			6.9	8.7	.....	.....	7.0	8.7	.....	7.1	9.5	.....	.....	7.2	8.7				
41-50			6.5	8.3	.....	.....	8.0	9.7	.....	7.0	9.4	.....	.....	7.5	8.3				
31-40			6.9	8.7	.....	.....	6.0	7.7	.....	6.6	9.0	.....	.....	6.5	8.7				
21-30			6.8	8.6	.....	.....	6.7	8.4	.....	6.8	9.2	.....	.....	6.7	8.6				
11-20			7.0	8.8	.....	.....	6.6	8.3	.....	6.8	9.2	.....	.....	6.6	8.8				

TABLE 2.—*Summary of growth of the Big Tree—Continued.*

Date of decade.	A. Trees in dry situations (Table 1A).				B. Trees in moist situations (Table 1B).				C. Trees in dry and moist situations (Tables 1A, 1B).			D. Trees in all kinds of situations; all trees be- longing to Huntington's (1914, pp. 311-322) groups.			
	Groups.	No. of measurements.	Curve 1		Groups.	No. of measurements.	Curve 2		No. of measurements.	Curve 3		Groups.	No. of measurements.	Curve 4	
			Average growth.				Average growth.			Average growth.				Average growth.	
1-10	18, 20-23, 25, 27	52	7.0	8.8	21-24, 26, 30, 31	28	6.2	7.9	80	6.7	9.1	21 to 31	69	6.1	6.3
10-1	20-23, 25, 27	43	6.6	8.3	22-24, 26, 30, 31	21	6.0	7.7	64	6.4	8.7	22 to 31	52	6.1	6.5
20-11	.....	.....	6.6	8.3	.....	.....	7.1	8.8	.....	6.8	9.1	.....	.....	6.3	6.7
30-21	.....	.....	7.3	9.0	.....	.....	6.6	8.3	.....	7.1	9.4	.....	.....	5.9	6.3
40-31	.....	.....	6.7	8.4	.....	.....	6.7	8.4	.....	6.7	9.1	.....	.....	5.9	6.3
50-41	.....	.....	6.6	8.3	.....	.....	6.7	8.4	.....	6.6	8.9	.....	.....	5.9	6.3
60-51	.....	.....	6.3	8.0	.....	.....	6.7	8.4	.....	6.4	8.7	.....	.....	5.8	6.2
70-61	.....	.....	6.4	8.1	.....	.....	6.3	8.0	.....	6.4	8.7	.....	.....	6.0	6.4
80-71	20-23, 25, 27	43	6.6	8.3	.....	.....	6.4	8.1	64	6.6	8.9	.....	.....	6.3	6.7
90-81	20, 22, 23, 25, 27	35	6.4	8.1	.....	.....	7.0	8.7	56	6.7	9.0	22 to 31	52	6.8	7.2
00-91	20, 22, 23, 25, 27	35	6.1	7.8	.....	.....	7.3	9.0	56	6.5	8.8	23 to 31	28	5.9	6.3
10-101	22, 23, 25, 27	20	5.7	7.4	.....	.....	6.6	8.3	41	6.1	8.5	.....	.....	5.9	6.3
20-11	.....	.....	5.1	6.8	.....	.....	6.9	8.6	.....	6.0	8.4	.....	.....	6.0	6.4
30-21	.....	.....	5.6	7.3	.....	.....	6.6	8.3	.....	6.1	8.5	.....	.....	5.5	5.9
40-31	.....	.....	5.3	7.0	.....	.....	7.4	9.1	.....	6.3	8.7	.....	.....	5.2	5.6
50-41	.....	.....	5.7	7.4	.....	.....	6.8	8.5	.....	6.2	8.6	.....	.....	5.4	5.8
60-51	.....	.....	6.0	7.7	.....	.....	6.3	8.0	.....	6.2	8.6	.....	.....	6.4	6.8
70-61	.....	.....	6.0	7.7	.....	.....	6.7	8.4	.....	6.3	8.7	.....	.....	5.9	6.3
80-71	.....	.....	6.1	7.8	.....	.....	6.9	8.6	.....	6.5	8.9	.....	.....	6.2	6.6
90-81	.....	.....	5.5	7.2	.....	.....	6.6	8.3	.....	6.0	8.4	.....	.....	5.8	6.2
00-191	22, 23, 25, 27	20	6.0	7.7	22-24, 26, 30, 31	21	7.2	8.9	41	6.1	8.5	23 to 31	28	6.3	6.7
10-201	22, 23, 27	16	6.6	8.4	22, 24, 26, 30, 31	17	6.3	8.0	33	6.4	8.6	24, 26-31	13	5.5	6.6
20-11	.....	.....	6.6	8.4	.....	.....	6.6	8.3	.....	6.6	8.8	.....	.....	5.5	6.6
30-21	.....	.....	7.1	8.9	.....	.....	6.2	7.9	.....	6.6	8.8	.....	.....	6.1	7.2
40-31	.....	.....	8.0	9.8	.....	.....	6.4	8.1	.....	7.2	9.4	.....	.....	5.4	6.5
50-41	.....	.....	8.8	10.6	.....	.....	7.7	9.4	.....	8.3	10.5	.....	.....	6.7	7.8
60-51	.....	.....	10.3	12.1	.....	.....	7.4	9.1	.....	9.0	11.2	.....	.....	5.7	6.8
70-61	.....	.....	8.5	10.3	.....	.....	6.7	8.4	.....	7.6	9.8	.....	.....	6.0	7.1
80-71	.....	.....	9.8	11.6	.....	.....	6.7	8.4	.....	8.0	10.2	.....	.....	6.5	7.6
90-81	.....	.....	3.4	5.2	.....	.....	8.2	9.9	.....	6.0	8.2	.....	.....	6.6	7.7
00-291	.....	.....	2.5	4.3	22, 24, 26, 30, 31	17	7.3	9.0	33	5.0	7.2	.....	.....	5.6	6.7
10-301	.....	.....	2.6	4.4	24, 26, 30, 31	7	6.3	9.3	23	3.7	6.5	.....	.....	5.5	6.6
20-11	.....	.....	2.7	4.5	.....	.....	5.8	8.8	.....	3.7	6.5	.....	.....	5.4	6.5
30-21	.....	.....	4.1	5.9	.....	.....	7.0	10.0	.....	5.0	7.8	.....	.....	6.1	7.2
40-31	.....	.....	3.1	4.9	.....	.....	7.4	10.4	.....	4.4	7.2	.....	.....	6.4	7.5
50-41	.....	.....	3.3	5.1	.....	.....	7.9	10.9	.....	4.7	7.5	.....	.....	6.7	7.1

TABLE 2.—*Summary of growth of the Big Tree—Continued.*

Date of decade.	A. Trees in dry situations (Table 1A).				B. Trees in moist situations (Table 1B).				C. Trees in dry and moist situations (Tables 1A, 1B).			D. Trees in all kinds of situations; all trees belonging to Huntington groups. (1914, pp. 311-322)			
	Groups.	b No. of measurements.	c	d	Groups.	f No. of measurements.	g	h	i No. of measurements.	j	k	Groups.	m No. of measurements.	n	
			Curve 1	Curve 2			Curve 3	Average growth.		Average growth.	Average growth.			Average growth.	
360-51	22, 23, 27	16	4.2	6.0	24, 26, 30, 31	7	7.0	10.0	23	5.1	7.9	24, 26-31	13	6.5	7.0
370-61			5.2	7.0			5.6	8.6		5.3	8.1			5.5	6.0
380-71			9.3	11.1			5.9	8.9		8.2	11.0			5.8	6.0
390-81			6.9	8.7			5.9	8.9		6.6	9.4			6.5	7.0
400-391	22, 23, 27	16	9.2	11.0			7.6	10.6	23	8.7	11.5	24, 26-31	13	5.8	6.0
410-401	23, 27	4	8.0	9.6			7.7	10.7	11	8.8	11.9	27 to 31	6	6.2	6.0
420-11			9.3	10.9			5.7	8.7		7.0	10.1			6.8	7.0
430-21			6.3	7.9			6.7	9.7		6.5	9.6			7.2	7.0
440-31			4.3	5.9			7.7	10.7		6.5	9.6			7.0	7.0
450-41			5.5	7.1	24, 26, 30, 31	7	8.8	11.8	11	7.6	10.7			9.2	9.0
460-51			5.5	7.1	26, 30, 31	5	6.8	9.8	9	6.2	8.8			7.5	8.0
470-61			6.5	8.1			7.0	10.0		6.8	9.4			7.2	7.0
480-71			5.8	7.4			7.4	10.4		8.8	11.4			6.7	7.0
490-81			5.5	7.1			6.8	9.8		6.2	8.8			6.5	7.0
500-491	23, 27	4	4.3	5.9			5.8	8.8	9	5.4	8.0			5.1	5.0
510-501	27	2	5.0	4.2			5.6	8.6	7	5.4	8.0			5.3	6.0
520-11			6.5	5.7			5.2	8.2		5.6	8.2			6.5	7.0
530-21			6.0	5.2			7.2	10.2		5.7	8.3			6.8	7.0
540-31			3.0	2.2			5.8	8.8		5.0	7.6			5.3	6.0
550-41			7.5	6.7			6.0	9.0		6.4	9.0			6.2	6.0
560-51			4.0	3.2			4.8	7.8		4.6	7.2			4.7	5.0
570-61			6.0	5.2			4.8	7.8		5.1	7.7			5.1	5.0
580-71			6.0	5.2			7.8	10.8		7.3	9.9			6.7	7.0
590-81			8.0	7.2			6.0	9.0		6.4	9.0			6.7	7.0
600-591			7.0	6.2	26, 30, 31	5	5.8	8.8	7	6.1	8.7			6.0	6.0
610-601			6.0	5.2	30, 31	3	5.3	8.5	5	5.6	8.0			5.1	5.0
620-11			6.0	5.2			6.3	9.5		6.2	8.6			5.7	6.0
630-21			5.5	4.7			6.7	9.9		6.2	8.6			6.2	6.0
640-31			8.5	7.7			7.7	10.9		8.0	10.4			7.5	8.0
650-41			6.5	5.7			7.3	10.5		7.0	9.4			6.7	7.0
660-51			5.5	4.7			6.0	9.2		5.8	8.2			5.5	6.0
670-61			9.0	8.2			6.7	9.9		7.6	10.0			7.4	8.0
680-71			5.0	4.2			7.0	10.2		6.2	8.6			6.0	6.0
690-81			6.0	5.2			5.7	8.9		5.8	8.2			5.3	6.0
700-691	27	2	3.5	2.7			5.7	8.9	5	4.8	7.2	27 to 31	6	5.4	6.0
710-701							5.0	8.2	3	5.0	7.2	30, 31	3	5.0	5.0
720-11							4.7	7.9		4.7	6.9			4.7	5.0
730-21							4.3	7.5		4.3	6.5			4.3	4.0
740-31							4.3	7.5		4.3	6.5			4.3	4.0
750-41							5.7	8.9		5.7	7.9			5.7	6.0
760-51							4.0	7.2		4.0	6.2			4.0	4.0
770-61							4.7	7.9		4.7	6.9			4.7	5.0
780-71							5.3	8.5		5.3	7.5			5.3	5.0
790-81							5.0	8.2		5.0	7.2			5.0	5.0
800-791							5.0	8.2		5.0	7.2			5.0	5.0
810-801							7.7	10.9		7.7	9.9			7.7	8.0

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TREE GROWTH AND CLIMATIC INTERPRETATIONS.

BY ELLSWORTH HUNTINGTON,
of Yale University.

Three Text-figures.

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TREE GROWTH AND CLIMATIC INTERPRETATIONS.

PART I. SEQUOIAS AS A CLIMATIC YARDSTICK.

The growth of trees is becoming more and more widely recognized as one of the best means of measuring the climate of the past. We must, to be sure, rely on other evidence to determine whether the climate at the beginning of a tree's life was the same as when the tree was cut, but as a means of determining climatic fluctuations during its own life the tree is remarkably effective. So far as known, the *Sequoia washingtoniana* of the Sierra Nevadas in California is the most valuable tree for this purpose, for it is the oldest whose record can easily be read. Several sequoias over 3,000 years of age have already been measured, and it seems not unreasonable to hope that in due time these great trees may furnish a reliable climatic record for 4,000 years. If such a record is to be of much value, two main problems must be solved: First, we must determine beyond reasonable doubt the climatic conditions under which a given type of annual growth is made; and second, we must ascertain what these climatic conditions mean as to the climate of other parts of the world. To determine the first would be relatively easy, provided we had weather records from the region where the trees grow. The second is highly difficult, and may take many decades.

The purpose of the present paper is to discuss certain methods of studying these two problems, and then to consider the theoretical bearing of the results. The materials here employed comprise: (a) measurements of the annual growth of sequoias as given in Table I, page 328, of *The Climatic Factor*; (b) a similar table for a smaller number of trees given by Douglass in *Climatic Cycles and Tree Growth*, page 123; (c) records of precipitation in the United States and other countries; and (d) records of temperature in California.

The present study is limited to the relation of precipitation and temperature to tree growth from year to year. Other environmental conditions, such as insect pests, forest fires, shading in youth, and dominance in old age, need not be considered, because, in the long run, when many trees are used, they average out. Our final results depend on over 100 trees, all of which were vigorous and dominant during the time covered by the present investigation. None show appreciable signs of fires, or the ravages of insects. Other climatic conditions, such as wind and sunshine, although doubtless important, are probably so closely associated with temperature and precipitation that they can not easily be investigated separately.

The annual precipitation where the trees grow, at an altitude of about 6,000 feet, averages 40 to 60 inches. The four months from June to September are almost rainless and the days are hot in summer in spite of cool nights. Recurrent periods of perhaps eight months with an average precipitation of scarcely more than one inch per month apparently cause precipitation to assume great importance as a determinant of growth. The first device here used in comparing precipitation and growth is dot charts, but these are preliminary to correlation coefficients. This latter method assumes that the relation between precipitation and tree growth can be plotted as

a straight line; in other words, that a given increment of rain normally produces the same increment of growth, no matter whether it is added to a small or a great rainfall. This is not strictly true, for undoubtedly a sufficient excess of rain would not only check the growth of the trees but ultimately kill them. In practice, however, no such excess occurs, or at least so rarely that it may be disregarded. We shall find that under ordinary circumstances a given increase in rainfall probably produces an almost constant increase in tree growth.

In selecting the materials for our investigation two puzzling problems present themselves. One concerns the trees. It arises from the fact that Douglass suggests that in my data for the annual growth of sequoias one year is missing. His idea appears to be that the growth of the year when my samples were cut was so soft that it disappeared and was not measured. This might be possible if I had used stumps cut by the lumbermen early in the season. As a matter of fact, practically all the samples of wood used in making the table on page 328 in *The Climatic Factor* were cut from mature, but not old, trees which were still growing. They were cut about the middle of July, and after the growth of the year of cutting had made such progress that the rings for that year looked about as wide as those of earlier years. In order to make sure of this I have reexamined three of the original samples and three others from younger trees which were cut at the same time, these being all that are now available. I find that all six show on the outside a ring which appears to be almost complete except that it lacks the thin red band of harder wood which regularly is formed at the end of the season. In one of the young trees this red band is beginning to appear very slightly at one point. In other words, all the rings appear as if cut well on in the season, but before the tree's work for that particular year had come to an end. This

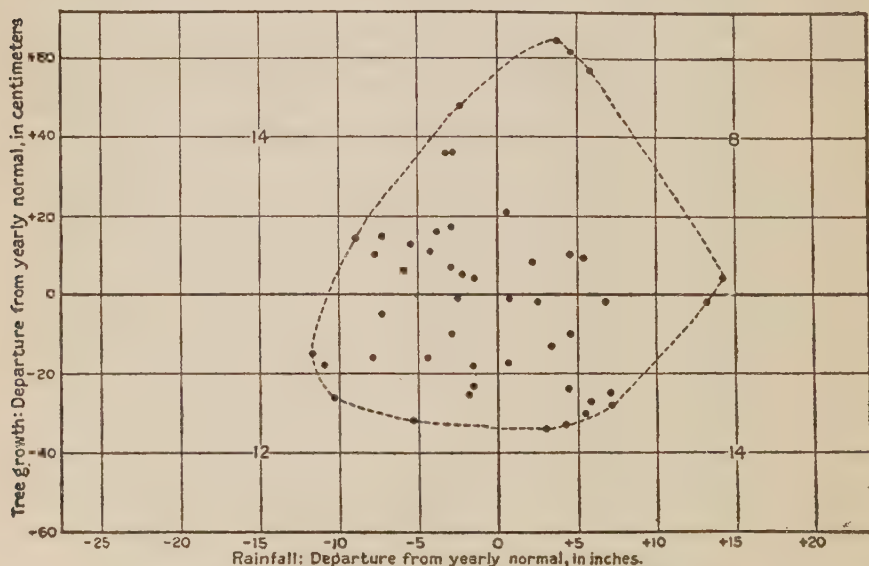


FIG. 1.—Dot chart of the relation between annual growth of 112 sequoias and rainfall at Sacramento during the preceding season, July to June, 1863-1910.

is important because it makes it practically certain that the rings belong to the years to which I have assigned them. The reason for discussing the matter will appear when we consider the remarkable way in which the growth of the trees lags behind the rainfall.

The other puzzling question is the choice of stations for rainfall data. Unfortunately there are no records of precipitation among the mountains near the trees, nor are there any long records in the neighboring lowlands; hence we are confronted by the question of whether to use (1) the short Fresno record, which is the nearest to the district where most of our trees are found, but which is not only short but belongs to an altitude about 6,000 feet below the trees; (2) the Sacramento record, which is long, but which comes from a region as low as Fresno and about 200 miles from the trees; or (3) the records from stations along the Southern Pacific Railway—the old Union Pacific—which have the advantage of being at altitudes like those of the trees, but which are not so long as the Sacramento record, although longer than that of Fresno, and which are even farther away than Sacramento. Inasmuch as the variations in rainfall at Fresno run closely parallel to those at Sacramento, it has not seemed worth while to employ the short Fresno record. Sacramento and a string of stations along the railroad have therefore been used.

DOT CHARTS OF RAINFALL AND TREE GROWTH.

Figures 1 and 2 sum up the main facts of the first part of our investigation. They are dot charts in which the horizontal distances represent the departures of the annual rainfall (figure 1) and of the average 10-year rainfall (figure 2) from the yearly normal. For example, in figure 1 the number +5 at the bottom indicates that during the season previous to the growth of a particular ring—that is, from July of the previous year to June of the year during which

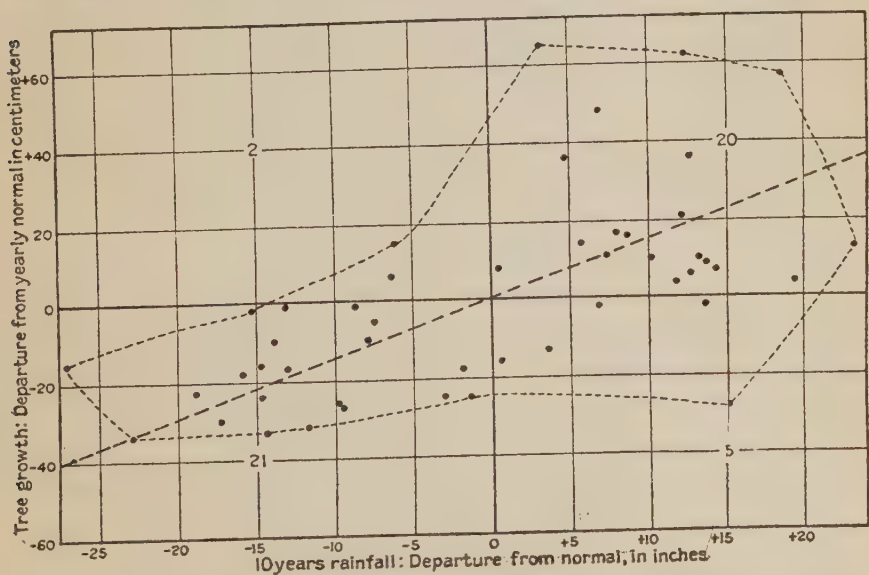


FIG. 2.—Dot chart of the relation between annual growth of 112 sequoias and rainfall at Sacramento during the 10 preceding years, 1863-1910.

the growth was made—the rainfall was 5 inches more than the yearly average. In figure 2 the meaning of the similar number is that during the ten seasons previous to the growth of a given ring the rainfall totaled 5 inches more than would fall in ten average years. The vertical scale in both figures indicates the departure of tree growth from the average of the period considered, namely, 1863 to 1910. For each year during this period a dot has been placed at the proper point to indicate both the rainfall and the rate of growth.

Let us interpret the two figures. In figure 1 the dots are fairly evenly distributed around the center. The differences in the numbers of dots in the four quarters of the diagram, as given near the center of each quarter, are small. They are not greater than might result from chance. Nowhere in the diagram is there anything to indicate that rainfall has any connection with the growth of the trees. In fact, so far as any connection is suggested, the excess of numbers in the upper left-hand and lower right-hand corners almost seems to give a hint that the trees grow better when there is not much rain.

In figure 2 the case is quite different. The great excess of dots in the lower left-hand and upper right-hand corners is much beyond what would normally happen as the result of accident. Moreover, the dots are to a considerable degree concentrated in a band with its center not far from the dotted line. This is especially marked in the left-hand part of the diagram, and would be almost equally marked on the other side if two or three exceptional years were omitted. In the left-hand portion, that is, when the rainfall is below normal, we may conclude without much doubt that when a considerable period, such as ten years, is considered, the rate of growth of the sequoias depends very closely upon the amount of rain. When rain is abundant the same relationship still prevails to a moderate degree, but other factors enter into the matter, as is indicated by the spreading of the dots in the right-hand half of the diagram. If the trees have more than the normal amount of rain, other factors, especially temperature, probably become more and more important. Beyond a certain limit, additional rain presumably ceases to be of much benefit, and temperature may become the main determinant of growth. That condition, however, appears to be reached so rarely that it may be disregarded at present. We conclude then that, when several years are considered together, the rainfall is the main determinant of the rate of growth.

CORRELATION COEFFICIENTS BETWEEN SEQUOIA GROWTH AND SACRAMENTO RAINFALL.

Since the relation between sequoia growth and the Sacramento rainfall seems to be represented by a straight line, we may use the method of correlation coefficients. It will be remembered that if two variable quantities are unrelated their correlation coefficient is practically zero; if they are related so that one increases or diminishes in exact proportion to the other, the coefficient is 1.00, while if one diminishes in exact proportion to the increase in the other, the coefficient is -1.00 . If the coefficient is four times the probable error, it means that there is one chance in 142 that the apparent relation is the result of accident, and a real relationship is probable. If the ratio between the coefficient and its probable error rises to 6, there is only one chance in 19,230 that the apparent relationship is accidental, and a real

relationship is practically certain. If the ratio rises to 8, the chances of accident are only one in about a billion and a half, and all possibility of accident can be disregarded.

Table 1 shows what happens when the method of correlation coefficients is applied to several groups of trees in comparison with the Sacramento rainfall. In column A, 80 trees which grew in moist locations show no appreciable correlation with the rainfall of the preceding autumn, winter, and spring, there being, of course, no summer rainfall. A correlation coefficient

TABLE 1.—Correlation coefficients between annual rainfall at Sacramento (July-June) and growth of *Sequoia washingtoniana* during succeeding seasons, 1863-1910.

r = correlation coefficient. r/e = ratio of coefficient to probable error.

Date of season of growth after preceding rainfall.	A.		B.		C.	
	80 sequoias in moist locations. Groups IA, IIA, IIIA, and VA. Climatic Factor, p. 328.		32 sequoias in dry locations. Groups IB and IIB. Climatic Factor, p. 328.		112 sequoias, being the trees of A and B combined.	
	r	r/e	r	r/e	r	r/e
1. First season.....	+0.023	0.2	+0.060	0.6	+0.127	1.3
2. Second season.....	+0.247	2.7	+0.337	3.9	+0.224	2.3
3. Third season.....	+0.288	3.2	+0.301	3.3	+0.337	3.8
4. Fourth season.....	+0.128	1.3	+0.100	1.0	+0.104	1.1
5. Fifth season.....	+0.006	0.1	-0.020	0.2	+0.073	0.7
6. Sixth season.....					+0.073	0.7
7. Seventh season.....					+0.116	1.1
8. Eighth season.....					+0.119	1.2
9. Ninth season.....					+0.210	2.1
10. Tenth season.....					+0.075	0.7
11. Eleventh season.....					+0.098	0.9
12. Twelfth season.....					+0.131	1.2
13. Thirteenth season.....					+0.066	0.6

of 0.247, which is 2.7 times the probable error, suggests a relationship to the rainfall of the second season before, while a coefficient of 0.288 in the third year strengthens this suggestion. Then the apparent relationship declines. None of these correlation coefficients is large enough to be conclusive, but the regular way in which they rise and fall may be significant. It looks as if the growth of a given year, say, 1923, had nothing to do with the rainfall of the preceding season from July 1922 to June 1923, but was influenced by the rainfall of the season of 1921-1922 and still more by that of 1920-1921. In column B, 32 trees growing in dry locations show the same relationship to rainfall as do the trees of column A, except that the highest coefficient is found for the second instead of the third season before the time of growth, and is slightly higher than in the other case. In column C the two groups, A and B, have been combined, and the coefficients computed between rainfall and the tree growth for thirteen successive years. The highest coefficient is about as in the other columns. The significant fact here is that every one of the thirteen coefficients is positive, although all are small.

Before attempting to explain table 1 let us consider table 2. Here the same groups of sequoias have been compared, not with the rainfall of single seasons except in the upper entry, but with the combined rainfall of two, three, or more preceding seasons up to ten. All show the same feature, namely, that when tree growth is compared with the rainfall of more than one season, the correlation coefficients rise greatly. Notice that, in the columns showing the ratio between the coefficients and their probable errors, most of the entries are above 4.0; every column has at least one entry above 6.0; and three columns have entries above 8.0. All this means that there is literally not one chance in billions or trillions that we are being misled by accidents in our conclusion, not only that tree growth, in part at least, depends on rainfall, but that there is a marked lag in the relationship. Note also that the dry trees, columns B and D, are influenced by the rainfall of fewer seasons than are the moist trees, only four or five against ten or more for the moist trees.

TABLE 2.—Correlation coefficients between annual growth of sequoias and rainfall at Sacramento during preceding seasons, 1863-1910.

r = Correlation coefficient. r/e = Ratio of coefficient to probable error.

Number of preceding seasons whose combined rainfall is compared with growth in final summer.	A.		B.		C.		D.	
	80 sequoias in moist locations. (Groups IA, IIA, IIIA, and VA.)		32 sequoias in dry locations. (Groups IB and IIB.)		112 sequoias in mixed locations. (A and B combined.)		18 sequoias in dry locations. (Group IIB.)	
	r	r/e	r	r/e	r	r/e	r	r/e
1. One season.....	+0.023	0.2	+0.060	0.6	+0.127	1.3	-0.059	0.6
2. Two seasons.....			+0.300	3.4	+0.217	2.2	+0.288	3.2
3. Three seasons.....			+0.420	5.4	+0.368	4.3	+0.570	8.7
4. Four seasons.....			+0.482	6.4	+0.401	4.8	+0.470	6.2
5. Five seasons.....			+0.475	6.3	+0.391	4.7		
6. Six seasons.....					+0.440	5.3		
7. Seven seasons.....					+0.459	5.6		
8. Eight seasons.....					+0.500	6.4		
9. Nine seasons.....					+0.575	8.8		
10. Ten seasons.....	+0.605	9.8			+0.577	8.8		

Thus far we have been using the record of seasonal rainfall (July to June) for the years 1863-4 to 1909-10. The record ends with the last year for which tree growth is given in *The Climatic Factor*. It begins at what I supposed to be the earliest date for which the Sacramento record is reliable. After these pages were in type, however, I learned from Dr. McAdie of Blue Hill Observatory, formerly head of the Weather Bureau station at San Francisco, that the record as far back as 1849-50, as given in Bulletin L of the Weather Bureau, is unusually reliable for so old a record. Hence, although it may not be perfect, I have used it to compute two new sets of coefficients corresponding to those in column C in Tables 1 and 2. The results are given in Table 3, where the ratios (r/e) from Tables 1 and 2 are added for comparison.

TABLE 3.—*Correlation coefficients between annual growth of 112 sequoias (Groups I, II, III, and V in The Climatic Factor) and seasonal precipitation at Sacramento.* r = Correlation coefficient; e = probable error; r/e = ratio of r to e .

Date of season of growth after season of rainfall.	1849-50 to 1909-10		1863-4 to 1909-10	Number of preceding seasons whose combined rainfall is compared with tree-growth in final season.	1849-50 to 1909-10		1863-4 to 1909-10
	r	e	r/e		r	e	r/e
1. First season.....	+0.063	0.7	1.3	One season.....	+0.063	0.7	1.3
2. Second season....	+ .212	2.6	2.3	Two seasons.....	+ .169	2.0	2.2
3. Third season....	+ .291	3.6	3.8	Three seasons....	+ .362	4.8	4.3
4. Fourth season....	+ .053	0.6	1.1	Four seasons.....	+ .385	5.1	4.8
5. Fifth season.....	+ .049	0.5	0.7	Five seasons.....	+ .410	5.5	4.7
6. Sixth season.....	— .091	1.0	0.7	Six seasons.....	+ .350	4.4	5.3
7. Seventh season..	+ .059	0.6	1.1	Seven seasons....	+ .347	4.3	5.6
8. Eighth season...	— .019	0.2	1.2	Eight seasons....	+ .296	3.6	6.4
9. Ninth season....	+ .254	2.9	2.1	Nine seasons.....	+ .421	5.5	8.8
10. Tenth season...	— .122	1.3	0.7	Ten seasons.....	+ .462	6.3	8.8

The difference between the coefficients derived from the longer and the shorter records is due largely to the fact that in the long record the first entry is 36.0 inches, a very heavy precipitation, which is rivaled in only one other year, while the second is 4.7, which is 3.1 inches lower than in any other year. As the Stockton and San Francisco records for the same year are almost equally low, this figure is probably correct. So far as the conclusions of the present study are concerned it makes no difference whether we use the longer or shorter Sacramento record. In either case the essential facts are, first, that when the rainfall of single seasons is considered, there is no apparent relation between the precipitation during a given rainy season and the growth during the succeeding summer. Nevertheless, when the precipitation is compared with the growth during the second and third years thereafter, an increasing relationship becomes evident. From the fourth year onward the coefficients drop to insignificant levels. The second fact is that no matter which record we use, there is a gradually increasing correlation when the rainfall of two, three, or more years is combined and compared with the growth at the end of the final rainy season. In both cases the highest correlations appear in the final figures where the precipitation of ten years is compared with the growth at the end of the tenth rainy season. In no case where the rainfall of several years is thus summed up, either in Table 2 or Table 3, does the ratio between the final coefficient and its probable error fall below 6.2. Such a ratio means that there is only about one chance in 50,000 that so large a coefficient would occur accidentally. In a case like this where independent groups of trees give the same result when compared with two rainfall records of different lengths, and where some coefficients rise to eight or almost ten times the probable error, the chances that we may be misled by an accidental agreement sink to only one in billions. The evidence of a close relationship becomes still more significant when we remember that although the variations in rainfall at Sacramento resemble those at the home of the

Big Trees, there are important local differences. If the record of precipitation among the Big Trees were available it is almost certain that the correlation would be still closer. Hence our first conclusion is that the growth of the trees unquestionably bears a close relationship to the actual rainfall where they grow.

The second conclusion derived from Tables 1 to 3 is that there is a considerable lag between the time when rain falls and the time when it becomes effective in stimulating the growth of the trees. Neither the trees growing in dry locations nor those in moist seem, as a rule, to feel any effect of the precipitation of the winter and spring just preceding the season of growth, although this rule probably breaks down in individual cases. In both groups of trees the rainfall of the second and third preceding seasons is the most important, the dry trees showing the effect of rain a little sooner than the others. In the two sets combined, but presumably mainly in the trees growing in moist locations, there is some relation between the rate of growth and the rainfall during ten or twelve preceding years. Of course precipitation produces its main effect during the second or third seasons after it is received, as is clear from Table 1. What we are here concerned with, however, is not merely this fact, but the further fact that the growth of the trees during many succeeding years also appears to show a slight effect of the rainfall. This delayed effect presumably arises from two causes. In the first place, botanists have lately discovered that trees and other perennial plants are much more like animals than was formerly supposed. They store up fat, for example, and use it in producing the seeds and growth of the next year. In the second place, practically all the sequoias grow in deep soil, and the great majority are located near the bottoms of the slopes rather than near the crests. Thus their roots penetrate deeply into soil that is practically always moist except during periods of unusual drought. In the deeper soil, whence the trees draw much of their moisture, the water derived from the snowfall of a given winter does not at once replace that of preceding seasons, even where the trees grow in what are called dry places. At least one season is required for it to percolate down and become effective. The majority of the sequoias grow in moist places—that is, on the bottom of little valleys, where often there are streams and swamps during much of the summer. Nevertheless, a large number of these streams and swamps become dry during the latter parts of the rainless summer, even in ordinary years. In dry years, such as 1923-4 and 1880-81, when there is little snow on the mountains, practically all the smaller streams and swamps dry up, and for several months during the summer the sequoias stand in soil whose upper part is relatively dry. When several dry years come in succession the underground water is seriously depleted even in the deeper portions of the soil. At the end of such a period, even in the places that are fairly well watered, it apparently takes two or three years for the melted snow fully to saturate all parts of the soil again, and to seep down from the upper slopes to the sequoias, or at least for the trees to recover their strength after the soil has again become saturated. In general our correlation coefficients seem to indicate that on an average it takes two or three years for the precipitation of a given year on the upper parts of the slopes to seep down through the soil to the places where the sequoias grow and there to become fully

effective in respect to the growth of woody layers. Moreover, the effect of extreme years, either directly through seepage, or indirectly through the stored food of the trees, may not come wholly to an end for ten or a dozen years. Thus, although there is strong evidence that the growth of the sequoias furnishes a reliable indication of the major variations in precipitation, it does not furnish a reliable indication as to individual years, but only as to groups of from two to a dozen, according to the location of the trees.

CORRELATION BETWEEN SEQUOIA GROWTH AND RAINFALL FARTHER AWAY THAN SACRAMENTO.

Since Sacramento is so low, being practically at sea-level, it seems probable that stations at a higher altitude may have a precipitation more closely like that of the home of the Big Trees. In order to test this, table 4 has been prepared. Here the growth of the trees is compared with the rainfall for five preceding seasons at San Bernardino, 200 miles to the southeast and at five stations along the old Union Pacific Railroad—the present Southern Pacific—at distances of 200 to 300 miles to the northwest and north. The results speak for themselves. The rainfall at San Bernardino, and at Colfax part way up the westward slope of the Sierras and at Summit at the top of the slope shows no significant correlation with the growth of the sequoias, for the coefficients are scarcely larger than the probable errors, as appears in the second column of table 4. At Truckee, however, just beyond the crest of the

TABLE 4.—*Correlation coefficients between annual growth of 112 sequoias and rainfall of five preceding seasons at California and Nevada stations. (1871–1909 in most cases.)*

Station.	Altitude in feet.	Correlation coefficient.	Ratio of coefficient to probable error.
Sacramento.....	70	+0.391	4.7 (1859–1910)
San Bernardino.....	1,050	+0.177	1.7
Colfax.....	2,400	+0.122	1.1
Summit.....	7,000	+0.148	1.3
Truckee.....	5,800	+0.300	2.9
Boca.....	5,500	+0.492	5.7
Winnemucca.....	4,300	+0.435	4.6

Sierras, the coefficient rises appreciably, becoming nearly three times the probable error, while at Boca a little farther down the east slope, but still among the mountains, the relation between tree growth and rainfall becomes strong, being decidedly greater than at Sacramento. This continues out over the dry basin of Nevada at least as far as Winnemucca. Judging from these figures, it would seem that near the California coast there is a belt where the rainfall varies in fairly close harmony with that of the sequoia region; then comes a belt along the west slope of the Sierras where the seasonal variations of rainfall are somewhat different, and then another belt where the rainfall has what may be called the sequoia character. This belt apparently lies on the west side of the Sierras in the sequoia region, but begins just east of them farther north and continues over into Nevada. The whole matter needs further investigation, but unfortunately little can be done until rainfall records are available close to the sequoias. It is earnestly to be

hoped that the efforts of the Weather Bureau and Forest Service will in due time give us records from three or four such stations. Yet even with the present records it seems highly important that Boca and Winnemucca, as well as Sacramento, show correlation coefficients of significant magnitude.

RELATION OF SEQUOIA GROWTH TO VARIATIONS OF TEMPERATURE.

The next step in our investigation is to discover the extent and nature of whatever relation there may be between the growth of the sequoias and variations in temperature. For this purpose we shall use the record at Sacramento. On the whole, the variations of temperature in the region surrounding the Sierra are more uniform than those of precipitation. For example, the correlation coefficient between the annual temperatures for 28 years at Sacramento in the Great Valley of California and at Winnemucca, at an altitude of 4,300 feet on the other side of the Sierra toward the center of Nevada, rises to the high level of $+0.788$ (± 0.048). In the same way a coefficient of $+0.662$ (± 0.066) is obtained when the yearly temperatures at Sacramento for the 30 years given in Bulletin L of the United States Weather Bureau (*Climatology of California*) are compared with the average of two neighboring stations at high altitudes on the Southern Pacific Railway near the crest of the Sierra, namely Truckee, altitude 5,800 feet, and Boca 5,300. Individually these two stations give much lower coefficients, namely Truckee $+0.380$ (± 0.105) and Boca $+0.544$ (± 0.086). This illustrates the fact that among the mountains there are great local variations not only in precipitation, but in temperature. Nevertheless, when we consider a fairly large area, such as that in which grew the trees here used, and especially when we consider a fairly long period, the general variations of temperature in the high Sierra appear to be in fairly close harmony with those of lowland stations like Sacramento, on the one side, and plateau stations like Winnemucca, on the other. Hence, although the Sacramento record is not perfectly in accord with the variations of temperature among the Big Trees, it affords at least a fair approximation—probably a better approximation than the parallel record of precipitation.

Let us first compare the Sacramento temperature during different groups of months with the growth of the sequoias during the contemporary or succeeding summers. This is done in Table 5 where Section A gives the correlation coefficients, while Section B gives the corresponding ratios between the coefficients and their probable errors.

In this table let us begin with the period from January to March, line 2. The first entry, $+0.014$, means that there is no appreciable relation between the temperature from January to March and the growth of the trees during the succeeding summer. The coefficient is not only insignificant in itself, but it is only 0.2 as large as the probable error, as appears in the left hand entry of line 2 in Section B. The second entry in line 2 of Section A, $+0.012$, likewise affords no hint of any relation between winter temperature and the growth during the *second* succeeding summer. The third entry, however, -0.245 , suggests a negative relationship between growth and the winter temperature two and one half years previously. A similar coefficient for the next year, -0.243 , strengthens this suggestion. Since these two coeffi-

cients are 2.9 times the probable error, there is one chance in 18 that either one of them is accidental. There is much less chance that two such coefficients would arise together, and that the coefficients in the whole of line 2 would rise symmetrically to a climax three years after the given temperatures, and would then fall with similar symmetry. Thus, while line 2 does not prove a delayed relationship between temperature and growth, it raises a presumption of such a relationship.

TABLE 5.—Correlation between temperature at Sacramento and annual growth of 112 sequoia trees (Groups I, II, III, and V), 1853-1910.

Section A.—Correlation coefficients.						
Period used for temperature.	Season (year) of tree growth in reference to temperature.					
	1	2	3	4	5	6
1. October-December (preceding growth).....	+0.302	-0.013	-0.138	-0.183	-0.178	-0.082
2. January-March.....	+ .014	+ .012	- .245	- .243	- .176	- .116
3. April-June.....	+ .117	+ .063	- .279	- .206	- .094	+ .061
4. July-September.....	+ .192	+ .090	+ .077	+ .150	+ .160	+ .143
5. October-December (after growth).....	+ .063	.....	.....	.....	.....	.....
6. April-September.....	+ .230	.....	.....	.....	.....	.....
7. October-March.....	+ .256	.....	.....	.....	.....	.....
8. October-December and April-September.....	+ .332	+ .092	- .258	- .183	- .094	- .037
9. October-June.....	+ .197	+ .000	- .373	- .357	- .188	- .094
10. Year, July-June.....	+ .185	.....	.....	.....	.....	.....
11. Year, October-September.....	+ .277	+ .085	- .276	- .175	- .117	- .063
Section B.—Ratios between correlation coefficients and their probable errors. ¹						
Period used for temperature.	1	2	3	4	5	6
1. October-December (preceding growth).....	3.7	-0.1	-1.6	-2.1	-2.0	-0.9
2. January-March.....	0.2	0.1	-2.9	-2.9	-2.0	-1.3
3. April-June.....	1.3	0.7	-3.3	-2.4	-1.0	0.6
4. July-September.....	2.3	1.0	0.9	1.7	1.8	1.6
5. October-December (after growth).....	0.7	.....	.....	.....	.....	.....
6. April-September.....	2.7	.....	.....	.....	.....	.....
7. October-March.....	3.1	.....	.....	.....	.....	.....
8. October-December and April-September.....	5.1	1.0	-3.0	-2.1	-1.0	-0.4
9. October-June.....	2.3	0.0	-4.8	-4.5	-2.1	-1.0
10. Year, July-June.....	2.2	.....	.....	.....	.....	.....
11. Year, October-September.....	3.4	1.0	-3.3	-2.0	-1.3	-0.7

¹ The minus signs prefixed to certain ratios are those of the corresponding coefficients.

This presumption is strengthened by line 3, showing the coefficients between the temperature from April to June and the growth during that period and the ensuing summer. Beginning with a positive value of $+0.117$ (1.3 times the probable error) the coefficients become negative with a maximum of -0.279 for the third year. As this is 3.3 times the probable error, there is one chance in 37 that a single coefficient of this size may be accidental. Here again the symmetry of the coefficients adds to the probability that they represent a real relationship. Passing over the coefficients for July to September for the moment, we find that those for October to December *before* the time of growth, line 1, display the same systematic quality as those for the winter and spring. The chief difference is that, when the autumn temperature is compared with the growth of the trees, the *positive* coefficient ($+0.302$) for the first year's growth is fairly large, while the negative coefficients for the growth of later summers are smaller than in the other cases. There is one chance in 78 that a coefficient of 0.302 might occur accidentally. Much more important than this, and much less likely to be the result of accident, is the systematic arrangement of the coefficients for all three seasons — positive values for the first season of tree growth, a regular transition to negative values of considerable size for the third and fourth seasons, and then values which again diminish toward zero.

At this point a parenthetical remark is appropriate. Line 5 of Table 5 gives the coefficient between the temperature of the months from October to December and the tree growth of the *preceding* summer. The coefficient ($+0.063$) is only 0.7 times the probable error, and indicates no relationship whatever. The contrast between this insignificant coefficient and the fairly large coefficient of $+0.302$ when the temperature of these same months is compared with the growth during the following summer makes it quite clear that there has been no mistake in assigning dates to our rings of growth as suggested by Douglass. The impossibility of such a mistake becomes still clearer when line 8 with a coefficient of $+0.382$ (5.1 times the probable error) is taken into account.

Turning again to our interpretation of Table 5, lines 5, 6, and 7 need no further comment. Passing by line 8, we find that in line 9 the temperature of the nine cooler months has been compared with the tree growth. The coefficients are quite as systematic as those for the individual quarters of the year, but rise much higher. There is less than one chance in 800 that a single coefficient as large as that of the third year's growth (-0.373) should be obtained accidentally, and only one chance in hundreds of thousands that mere chance would give two coefficients of practically this size, and that these would fall in a systematic sequence. From all this we may conclude with considerable certainty that although relatively warm weather during the cooler months exerts in general a slight beneficial effect upon the growth of the Big Trees during the succeeding warm months, such weather has a much more important effect in diminishing the growth of the trees during the third and fourth summers after its occurrence. In other words, we have here a delayed relationship of the same kind and the same general magnitude as that which we have already found in the case of precipitation, but this delayed relationship is reversed.

Before discussing the causes of this peculiar phenomenon let us examine the coefficients for July to September (line 4 in Table 5). Here the conditions are quite different from those of the other seasons; all the coefficients, though small, are positive. In this respect they resemble those between rainfall and tree growth, as given in Table 1. They differ from those, however, because they diminish in size after the first year. Moreover, they are not cumulative, as appears from the following coefficients where the average temperature from July to September for one, two, three, and four years is compared with the growth of the trees during the final summer:

$$(1) = +0.192 \quad (2) = +0.158 \quad (3) = +0.125 \quad (4) = +0.177.$$

As none of these coefficients, except the first, rises to twice the probable error, and as there is no hint of any cumulative effect such as is so marked in the case of precipitation in Tables 2 and 3, it seems safe to conclude that the temperature of the growing season has no appreciable effect on growth of succeeding seasons. How great the effect is upon the growth of its own season is not quite clear. If we consider the growing season as lasting from April to September, the correlation coefficient between temperature and growth is $+0.230$. This is only 2.7 times the probable error, and hence is of little significance. In fact the correlation (-0.256 , which is 3.1 times the probable error) of the growth of a given season with the temperature of the preceding winter (October to March) is stronger than the correlation with the temperature of the period of growth. Yet this is not so strong as the correlation between the temperature from October to January and the growth the following summer, $+0.302$. Even more puzzling is the fact that if the winter months of January to March are omitted, the correlation coefficient between tree growth and the temperature from October through December of the preceding year, and then from April to September of the year of growth, rises to the relatively high figure of $+0.382$, or 5.1 times the probable error—a figure so large as to afford a strong presumption of a relationship between temperature and growth. But this relationship can not be direct, for it is strongest from October to December after the growth of the trees for the year is completed and at a time when the ground is more or less frozen and snow-covered.

Before attempting to explain these seemingly contradictory features, attention should be called to the fact that the relation between precipitation and temperature in California is by no means such that a change in one means a corresponding change in the other. It is often mistakenly assumed that a decline in temperature is regularly accompanied by a decline in precipitation or vice versa. The facts do not bear this out. At Sacramento, for example, the correlation coefficient between the seasonal precipitation from July to June and the temperature for the same season from 1853-4 to 1909-10 amounts to only -0.064 , which is less than the probable error, ± 0.089 . What actually happens is that the precipitation is relatively great when the temperature is either unusually high or unusually low, while the precipitation is low during seasons when the temperature averages close to the normal. This is evident from the figures shown on the next page, where the rainy seasons (July to June) from 1853-4 to 1909-10 have been divided into three nearly equal groups on the basis of temperature.

Kind of years.	Temperature departures.	Average precipitation.	Average tree growth.
A. 20 coolest years.....	-0.4° F. or more	20.6 inches	2.95 mm.
B. 19 medium years.....	-0.3 to +0.3	17.3 inches	2.98 mm.
C. 18 warmest years	+0.4 or more	19.4 inches	3.01 mm.

It will be noticed that the tree growth varies in the same way as the temperature. This is what we should expect, since the temperature exerts an immediate effect upon the growth of the trees, whereas the effects of precipitation are delayed. But it must be remembered that it is the temperature of the preceding autumn which chiefly influences the trees, and it is that effect, as well as the delayed effect of an opposite character, which we are now to discuss.

The problem that confronts us is this: Although the temperature of the growing season plays a slight immediate part in stimulating the growth of the sequoias, its importance is not nearly so great as the delayed effect of precipitation, nor as its own delayed effect through some indirect method. The most reasonable explanation of this peculiarity seems to be as follows: Toward the end of the long rainless summer the ground becomes so dry that it is not favorable for the growth of trees. If the ground freezes early in the season, as happens in cold years; if the early precipitation takes the form of snow, as not infrequently happens; and if thereafter there is little warm weather to melt the snow, the ground has no opportunity to obtain a new supply of moisture until perhaps April or even May of the next year. If the spring also is cold, it may easily happen that the snow does not disappear and the ground become fully thawed until May or June. But during much and perhaps all of the period of cold weather the lower parts of the soil, where the roots of the trees seek for water, are becoming more and more dry by reason of a gradual downward seepage of the groundwater, and also by the slight transpiration which takes place from the trees even in winter. Thus at the end of the winter the soil is at its driest. Even after the ground is completely thawed, it may take weeks, possibly months, before the soil again becomes saturated. Thus the winter snows may, and apparently often do, have little or no value in stimulating the growth of the following summer. In a warm year, on the contrary, rains fall in the autumn before the ground is frozen, the early snows melt, and the water from both sources sinks into the ground. Thus the soil becomes saturated, and does not become seriously dry even though there is no water to replace the slow loss during the winter. In warm winters the growth of the next season is still further promoted by the fact that the ground does not freeze so deeply as usual. Therefore it melts relatively early in the spring, the melting snow can saturate it once more, and as soon as the temperature is high enough the trees can begin growth under favorable conditions of moisture. Thus there seems to be little difficulty in understanding why warmth in the preceding autumn, and to a less extent in the spring, exerts a stimulating effect which is considerably more important than the direct effect of warmth during the growing season.

Turning back to Table 5, it will be seen that we have explained the positive coefficients in the first column, and have shown why the autumn temperature has more effect upon growth than has the temperature of any other season. It

still remains to explain the high negative coefficients between temperature and the tree growth of the third and fourth seasons thereafter. The case is summed up in line 9 where the temperature for October to June gives negative coefficients of -0.373 and -0.357 when compared with the growth of the third and fourth years. If we compare the tree growth with the combined temperature for these same months during both the third and fourth preceding seasons the coefficient becomes -0.386 (5.0 times the probable error). This is not intrinsically a large coefficient, nor is it so large as the largest where precipitation and tree growth are compared. Nevertheless, it is large when we consider the following facts: (1) the weather record at Sacramento is only an imperfect approximation to that which would have been obtained if records had been kept where the trees actually grow; (2) the growth of the trees is influenced by many factors in addition to temperature; (3) the growth of the trees in any given season is influenced by the temperature of several different years.

The meaning of the negative coefficients seems to be this: A cold winter, as we have seen, keeps the ground relatively dry from autumn until late in the spring and may lessen the amount of moisture around the roots of the trees well into the summer. A warm winter, on the other hand, moistens the soil and gives the trees an immediate stimulus. At the same time it allows a relatively large percentage of the winter rains or melted snows to be lost by evaporation, or in larger measure by running off over frozen ground. In these ways, during a warm winter, a large share of the winter precipitation may be completely lost so far as the storage of water for future years is concerned. Much of the remainder is used for the immediate needs of the trees, but is not stored on the upper slopes in such a way that it can seep downward and keep the lower levels moist until the end of summer. How great the evaporation and melting of the snow may be, even in midwinter, is evident from the following facts gleaned from McAdie's *Rainfall of California*, published by the University of California. At Summit on the crest of the Sierra at an altitude of over 7,000 feet, the depth of the snow January 19, 1907, was 158 inches, but a month later it was only 84. The next year between March 7 and April, the depth diminished from 176 inches to 50; in 1910 there were 202 inches on January 27 and only 156 two days later. Practically all the snow thus lost is either evaporated, or runs off rapidly without sinking into the soil. In either case it is useless so far as the trees are concerned. Again, from 1907 to 1913 the ground at Summit was continuously covered with snow during the months of January to March. The loss of snow, as judged by the depth at intervals of two days, amounted to only 114 inches in 1912, in contrast with 283 in 1911. Of course a part of this difference was due to cloudiness, and a part to the fact that while it lies on the ground the snow settles downward under the influence of the sun and becomes more compact. Nevertheless, the fact remains that the temperature makes a great difference in the amount of snow which is evaporated, or which is melted and runs off while the ground is frozen. In other words, so far as tree growth is concerned, the chief function of the winter temperature seems to be to alter the amount of precipitation stored up as ground water.

Cold winters increase the supply thus stored; warm winters diminish it. There is no contradiction between this statement and our previous explanation

of why high temperature in the autumn and spring increases the amount of ground water. In that case we were talking of what happens when the ground is unfrozen, here we are talking of what happens when the ground is frozen. When the ground is unfrozen, high temperature in the autumn and spring serves to melt the snow and allow it to moisten the earth, thus increasing the supply of ground water. When the ground is frozen, a relatively high temperature, which may actually be far below freezing, diminishes the potential supply of ground water by allowing it to evaporate or run rapidly down over the frozen surface of the slopes to the valleys.

The process whereby ground water lags in its effect on tree growth has already been explained in connection with precipitation. It is not a mere accidental coincidence that Tables 1 and 5 both show a maximum effect during the third season after a given condition of precipitation or temperature. The coincidence seems to arise because in both tables we are dealing with the effect of ground water. Nor is it an accident that the next to the highest correlation comes in the second year in Table 1 and in the fourth in Table 5. On the contrary this seems to be one of those minor and wholly unexpected details which confirm an hypothesis because they were not thought of when the hypothesis was framed. By hypothesis, the delayed effect of temperature upon ground water ought to be greater at high altitudes than at low, because the alternate thawing and freezing are especially frequent at high altitudes and the duration of the frozen period is long. The hypothesis also ascribes the lag in the effect of precipitation to the fact that considerable time elapses while the water is percolating down the slopes to the places occupied by the trees. The seepage from the highest slopes naturally reaches the trees later than that from the lower slopes. Hence we should expect the influence of temperature upon ground water to make itself evident a little later than the corresponding influence of precipitation as a whole, and that is just what is shown by the correlation coefficients.

MEANING OF LONG SEQUOIA CURVES.

Having completed our discussion of the effect of precipitation and temperature upon tree growth, it behooves us to inquire into the meaning of the relatively large fluctuations in tree growth which cover centuries of time. That these fluctuations actually indicate corresponding fluctuations of climate is attested with new emphasis by Dr. Antevs in the preceding paper. But what kind of changes do they indicate? Is precipitation or temperature the main factor which they measure? Or do the two combine their effects in more or less equal measure? That both temperature and precipitation play some part in producing features like the marked rise in the tree curve in the fourteenth century can scarcely be doubted. Even though we have found no appreciable relation between rainfall and precipitation at Sacramento, it seems to me inevitable that any large changes in either factor must be accompanied by some change in the other. Nevertheless, the evidence of the palm and the vine in Palestine as set forth by Gregory in his article on *Is the Earth Drying Up* (Geographical Journal, 1914), and as Visser and I have shown in *Climatic Changes*, seems to join with other evidence in indicating that while considerable changes in rainfall may have taken place during historic times, the changes in temperature must have been slight.

The trees seem to point in the same direction. One reason for this statement is the fact that the highest correlation coefficients between precipitation and tree growth rise considerably higher than do the highest between temperature and tree growth, $+0.605$ against -0.386 , or if we use only the long records with their possible inaccuracy in the case of precipitation, $+0.462$ against -0.386 . More important than this is the fact that the correlation between tree growth and precipitation is always positive; increased rain is accompanied or followed by more rapid growth. The correlation between growth and temperature, on the contrary, is sometimes positive and sometimes negative. The two highest coefficients are $+0.382$ and -0.386 . In other words the immediate effect of high temperature in stimulating growth is approximately the same as the delayed effect through deficiency of ground water in retarding growth. Thus the two almost balance one another. The only way to draw reliable conclusions as to the past is to base them on the observed facts of the present. The observed facts of the present are that precipitation has a well-defined and uniform effect in stimulating the growth of the trees; temperature has a smaller although scarcely less well-defined effect, but the beneficial effects of high temperature in the first year are practically wiped out by the restriction of growth in later years through the diminished supply of ground water. Hence in a curve where ten years is the unit of time, as in our main curve of the sequoias, it appears reasonable to think that precipitation is the main factor. This seems to be a step toward solving the first of our main problems, namely that of determining beyond reasonable doubt the climatic conditions under which a given type of annual growth is made.

TREE GROWTH COMPARED WITH RAINFALL IN OTHER REGIONS.

The second of the main problems here presented by tree growth is the extent to which the growth of the sequoias can be used as a measure of the climate of the past in other regions. Table 6 is a first step toward answering this. Here the growth of 112 sequoias is compared with the summer rainfall of Tucson, Arizona, and with the total annual rainfall at Mexico City, which receives most of its rain in the summer. A similar comparison is made with the rainfall at Algiers and Naples, two stations in the central Mediterranean region which receive most of their rain in winter, and with the rainfall at Genoa in northern Italy, where there is rain at all seasons. The last comparison is with Jerusalem at the eastern end of the Mediterranean, where the rain is limited to the winter as sharply as in central and southern California, more sharply than at any of our other stations.

The summer rain at Tucson and the total rain of the whole year at Mexico City are alike in certain respects. At Tucson, the summer rain is the result of the heating of the great continental interior, the consequent indraft of air from the oceans, and its rise in a mid-continental area of low pressure. In Mexico the summer rain is the result of the northward migration of the sun and the consequent heating of the earth along a belt not far from the area where the sun's rays fall vertically. In both cases the rainfall is directly related to the heating power of the sun and does not depend to any appreciable degree upon the intermediary agency of the ordinary type of cyclonic storms. Thus variations in solar radiation, which may be an important cause of

variations in rainfall, would be expected to have approximately the same effect in both places. Whatever may be the truth in this respect, the summer rain at Tucson and Mexico City shows a distinct hint of varying in a fashion opposite to that of the growth of the sequoias. In neither case is the coefficient large enough to be conclusive. In Mexico City it rises to -0.354 , but this is only 3.1 times the probable error. The probable error, however, is very large because of the short rainfall record, only 28 complete overlapping 5-year periods being available for comparison with the tree growth of 28 successive years. If an equally large coefficient should be found as the result of a century of observations, the correlation coefficient would be six times the probable error. Thus, while the present figures are not conclusive, they suggest that in regions of summer rain of the equatorial and mid-continental types we may find that the sequoias afford some indication of the varia-

TABLE 6.—*Correlation coefficients between annual growth of 112 sequoias and rainfall of five preceding seasons at stations outside California and Nevada.*

Station.	Correlation coefficient.	Ratio of coefficient to probable error.
Tucson (June-Sept.).....	-0.271	2.6 (1867-1907)
Mexico City.....	-0.354	3.1 (1877-1908)
Algiers (3-year rain).....	-0.238	2.4 (1869-1910)
Naples (8-year rain).....	-0.132	1.3 (1851-1905)
Genoa (8-year rain).....	-0.010	0.1 (1851-1905)
Jerusalem (3-year rain).....	$+0.675$	12.7 (1869-1910)

tions in rainfall, rapid growth being correlated with low rainfall. This bears out the archaeological evidence of diminished rainfall in Yucatan and Guatemala at times when the California trees were growing rapidly, as explained in *The Climatic Factor*.

The next station in table 6 is Algiers with a negative coefficient of -0.238 (2.4 times the probable error). This is puzzling even though small, for we should not expect a negative coefficient, since the climate of Algiers is of the same type as that of California. The same is true to a less degree at Naples, where the coefficient is scarcely larger than the probable error. At Genoa, likewise, a coefficient of practically zero means that the climate there is of a different type from that of the Sierras. Finally, at Jerusalem the rainfall has an astonishingly high correlation with the growth of the trees, 0.675, which is 12.7 times the probable error, and is the highest correlation found in this whole investigation. We shall return to this shortly, but first let us consider Algiers and Naples a little further. Between Algiers and Jerusalem there is evidently a change from a small negative correlation to a large positive correlation. The line where the change occurs is presumably not far east of Naples. This suggests that we are here dealing with two areas of opposite types; one an oceanic area centering somewhere west of Algiers, perhaps in the Atlantic Ocean, and the other a continental area centering somewhere in western Asia, perhaps not far from Jerusalem, although we have no direct evidence as to where either center is found. The contrast is similar to that of which we have already found some evidence between a positive area within which lie the Big Trees and a negative area within which Mexico City appears to lie.

Such positive and negative areas are fast becoming recognized as one of the important features of the geography of climate. Hildebrandsson appears to have been the first to recognize them, but evidence regarding them has been found by many students, including especially Helland-Hansen and Nansen. Two characteristics of these areas concern us chiefly. One is that in areas of a given type the same kind of fluctuations in temperature, barometric pressure, or rainfall, as the case may be, take place simultaneously in regions far apart and separated by other types of regions. In areas of the other type the fluctuations are of a directly opposite character, for the temperature, pressure, or rainfall is high there when it is low in the other areas and vice versa. The second characteristic that now concerns us is that these positive and negative areas shift their positions and sizes a great deal. Certain key districts may perhaps always remain either positive or negative, but surrounding regions are sometimes neutral when on the border between a negative and a positive area, and sometimes assume either a positive or a negative character according to the shiftings of the central areas. The regions having this indeterminate character may be larger than those that belong to one or the other of the two definite types. In fact, if we consider long periods, it is probable that almost every part of the world belongs to the indeterminate type. A change of climate as great as that of the glacial period may alter the present distribution of areas of high and low pressure almost beyond recognition.

All this has a direct bearing on table 6. A study of climatic conditions 2,000 years ago suggests that southern Italy was then subject to pulsations like those which apparently prevailed farther east in Greece, Palestine, and neighboring regions. The same conclusion may apply to Algiers, but not so clearly. In Spain, so far as is yet known, it scarcely applies at all. At least such search as I have thus far been able to make discloses little evidence that ancient Spain suffered climatic pulsations like those which seem to be so clearly apparent at the other end of the Mediterranean. Now to-day, as we have seen, Jerusalem seems to belong to a type of climate where the pulsations are like those of California, while Algiers may perhaps belong to the opposite type and Naples may be almost on the border. It may be that 2,000 years ago the climatic area which now includes the eastern Mediterranean expanded so that it embraced southern Italy and perhaps Algiers but not Spain. As yet this is merely a suggestion. It is highly important, however, for unless it is borne in mind and carefully investigated, it will be very easy to draw wholly false conclusions. The probability is that during historic times certain widely separated areas have experienced similar climatic changes, while other widely separated areas have experienced the opposite type of changes. Between these two definite types, however, there have probably been some areas which have been relatively neutral, or have fallen sometimes under the sway of one type and sometimes of the other. Thus many different types of climatic history are not only possible but probable. The task of the investigator is first to find the centers of given types of change at present, then to delimit the areas which now belong to each type, and next to carry each area back as far as possible, determining whether its center has remained constant or has wandered, and how far it expanded or contracted.

JERUSALEM RAINFALL AND CALIFORNIA TREE GROWTH.

The correlation between tree growth in California and rainfall in Jerusalem is so high that it deserves further study. Table 7 gives the correlation between various groups of sequoias and the rainfall at Jerusalem for three preceding seasons. In general it appears that the larger the number of trees, the higher the correlation. Group A, however, is peculiar. This small group of trees growing in relatively dry locations shows a high correlation with the rainfall at Sacramento, 0.570 as given in table 2, but does not correlate significantly with the rainfall at Jerusalem. This is due largely to the year 1893, when the trees of this group grew unusually slowly, whereas those of other groups grew rapidly. It may illustrate the way in which accidents obscure important relationships. In table 7 the 11 trees measured by Douglass give a fairly high correlation with rainfall at Jerusalem, 0.453, which suggests that a few trees may be a good measure of the rainfall, even in distant places.

TABLE 7.—Correlation coefficients between 3-year rainfall at Jerusalem, 1861-1910, and average growth of various groups of sequoias.

No. of trees.	Source of data.	Environment.	Correlation coefficient.	Probable error.	Ratio.
			<i>r</i>	<i>e</i>	<i>r/e</i>
A 18	Climatic Factor, p. 328, Group IIB..	Dry	+0.182	±0.099	1.8
B 11	Douglass, p. 123.....	Mixed	+0.453	±0.078	5.8
C 80	Climatic Factor, p. 328, IA, IIA, IIIA, VA.....	Moist	+0.500	±0.073	6.8
D 101	Climatic Factor, p. 328, I, II, III..	Mixed	+0.616	±0.061	10.1
E 112	Climatic Factor, p. 328, I, II, III, V.....	Mixed	+0.675	±0.053	12.7

A larger number of trees is much better, however, for a few may fail to show a correlation which is otherwise well proven, as in the case of the 18 trees of A in table 7, while a larger number, as in the 112 of E in table 7, show a much higher correlation. It should be noted that the high correlation in E occurs even though the erratic 18 of group A are included.

Another point brought out by the trees of Group A is that although these trees do not agree well with the rainfall at Jerusalem and thus are exceptional, they show a high agreement with the rainfall at Sacramento, as appears in table 2. The whole thing illustrates the intricacy of the problem, and the value of dealing with large numbers of trees and long rainfall records.

Putting aside these perplexing aspects, let us examine table 8, where the rainfall at Jerusalem for overlapping periods of five years is compared with the similar rainfall at stations in California and Nevada. The stations here are the same as in table 4, where sequoia growth was compared with the rainfall of California and Nevada. The results are similar in most respects. San Bernardino shows no relation either to sequoia growth or to rainfall in Jerusalem. Colfax and Summit show somewhat higher correlations with Jerusalem than with the trees, Truckee is practically the same in both cases, but the coefficient is not high enough to be convincing. Sacramento and especially Boca show significant correlations, while Winnemucca fails to

have any clear relation to Jerusalem although its rainfall is highly correlated with the growth of the sequoias. It is worth noting that at five stations out of seven the correlation is higher when the rainfall of 5 years is used than when only 3 years are employed, while at Colfax the two coefficients are practically identical. At Boca the coefficient sinks almost to zero when the rainfall of single years is compared with that of Jerusalem. This seems to mean that while the longer swings of rainfall in Palestine and the Sierras agree fairly closely, the minor variations from year to year may take place independently.

One of the main results of our comparison thus far is that we find a significant agreement among four places, no matter which one we compare

TABLE 8.—*Correlation coefficients between rainfall at Jerusalem and at stations in California and Nevada. (1871-1909 in most cases, but 1859-1910 at Sacramento.)*

Station.	3-year rainfall.		5-year rainfall.	
	Correlation coefficient.	Ratio of coefficient to probable error.	Correlation coefficient.	Ratio of coefficient to probable error.
Sacramento.....	+0.230	2.2	+0.353 ¹	4.2
San Bernardino.....	+0.275	2.7	+0.177	1.6
Colfax.....	+0.311	3.1	+0.308	3.0
Summit.....	+0.099	0.9	+0.248 ¹	2.3
Truckee.....	+0.229	2.2	+0.337 ¹	3.3
Boca.....	+0.475	5.5	+0.604 ¹	8.0
Winnemucca.....	+0.235	2.2	+0.260 ¹	2.4

¹ Larger than for 3-year comparison.

with the other. Sacramento, Boca, the site of the Big Trees, and Jerusalem all seem to have had the same main fluctuations of rainfall during the last 40 or 50 years. In individual years they have indeed departed widely from one another, but this disagreement disappears when periods of several years are considered. If longer records were available it seems probable that we should find that the growth of the trees and the rainfall at Jerusalem agree with the rainfall at still other stations in California, as is suggested by the larger size of the coefficients in the 5-year than in the 3-year section of table 8. It is certain that the agreement among the California stations becomes greater as longer periods are considered.

But why should the rainfall at Jerusalem agree with both the sequoia growth and the rainfall at Boca better than does that of any station thus far tested in the United States? The answer may perhaps be found in the physical similarity of the two regions. Jerusalem lies in nearly the same latitude as the Big Trees, about 32° against 36.5°. Both lie at fairly high altitudes, 2,400 against 6,000 feet above sea-level, on the western margin of great continents just where the westerly winds from the ocean rise and give up their main load of vapor. In both places the rainfall is of the same type, abundant in winter but almost absent from May to October. A little north of Jerusalem in the Lebanon Mountains, latitude 34° N., the famous cedars grow in an environment still more like that of the Big Trees. The latitude,

altitude, and relation to the snow-line are almost identical, the temperature presumably differs only slightly, and the precipitation must be closely similar in seasonal distribution, and in the percentage which falls as snow, although probably Lebanon is the drier of the two.

Our studies suggest that in addition to all these resemblances, or perhaps because of them, the pulsations of climate from decade to decade and century to century in California and Lebanon have been closely similar. It is interesting to find that two such similar environments shelter two such similar kinds of trees. The sequoia and the cedar of Lebanon are similar not only in habit and size, but in age. Although none of the remaining small group of old cedars has ever been studied in detail, a member of the faculty of the American University at Beirut counted the rings in a broken limb, and concluded that they numbered at least 2,000. It is earnestly to be hoped that before many years the growth of these ancient giants may be carefully measured year by year. Even if the oldest cedars can not (and should not) be interfered with, younger trees are growing not many miles away and some of these may have an age of hundreds of years unless all were cut off during the World War. A study of these trees would be one of the most effective methods of testing the surprising agreement between the apparent climatic fluctuations in similar parts of Asia and North America.

POSITIVE AND NEGATIVE AREAS OF RAINFALL IN THE UNITED STATES.

In further studies of the significance of the Big Trees as a climatic yardstick, it seems clear that the distribution of positive and negative areas will play a large part. In the long run the best method of studying these may be by means of correlation coefficients so applied that they will test: (a) seasonal similarities of rainfall and temperature, the seasons being either the cooler and warmer halves of the year, or still smaller units; (b) yearly similarities; and (c) the similarities of either seasonal or annual rains when several years are used as the unit and the minor irregularities of short periods are thus eliminated. The work of collecting the necessary monthly data, which are published in most heterogeneous and scattered forms, is very great, for it is necessary in most cases to go to the original serial publications. Even when the necessary data are available, their tabulation and still more the working out of correlation coefficients will be the work of years.

Meanwhile a first approximation to the truth may perhaps be obtained in other ways.

Among the stations whose rainfall we have investigated, Boca seems to be the most significant in relation to the Big Trees. Unfortunately this is a small and unimportant station, and its records have not the authoritative character of those of regular Weather Bureau Stations. Nevertheless the Boca record has probably been kept with as much care as in the average cooperative station. The railroad, which originally kept the record, is vitally interested in the results, for Boca lies near the Truckee River, and the most exact data are needed in order to enable plans for irrigation to be made safely and intelligently.

Taking Boca, then, as our primary station, our purpose is to determine how far its rainfall fluctuates in harmony with that of other parts of the United States.

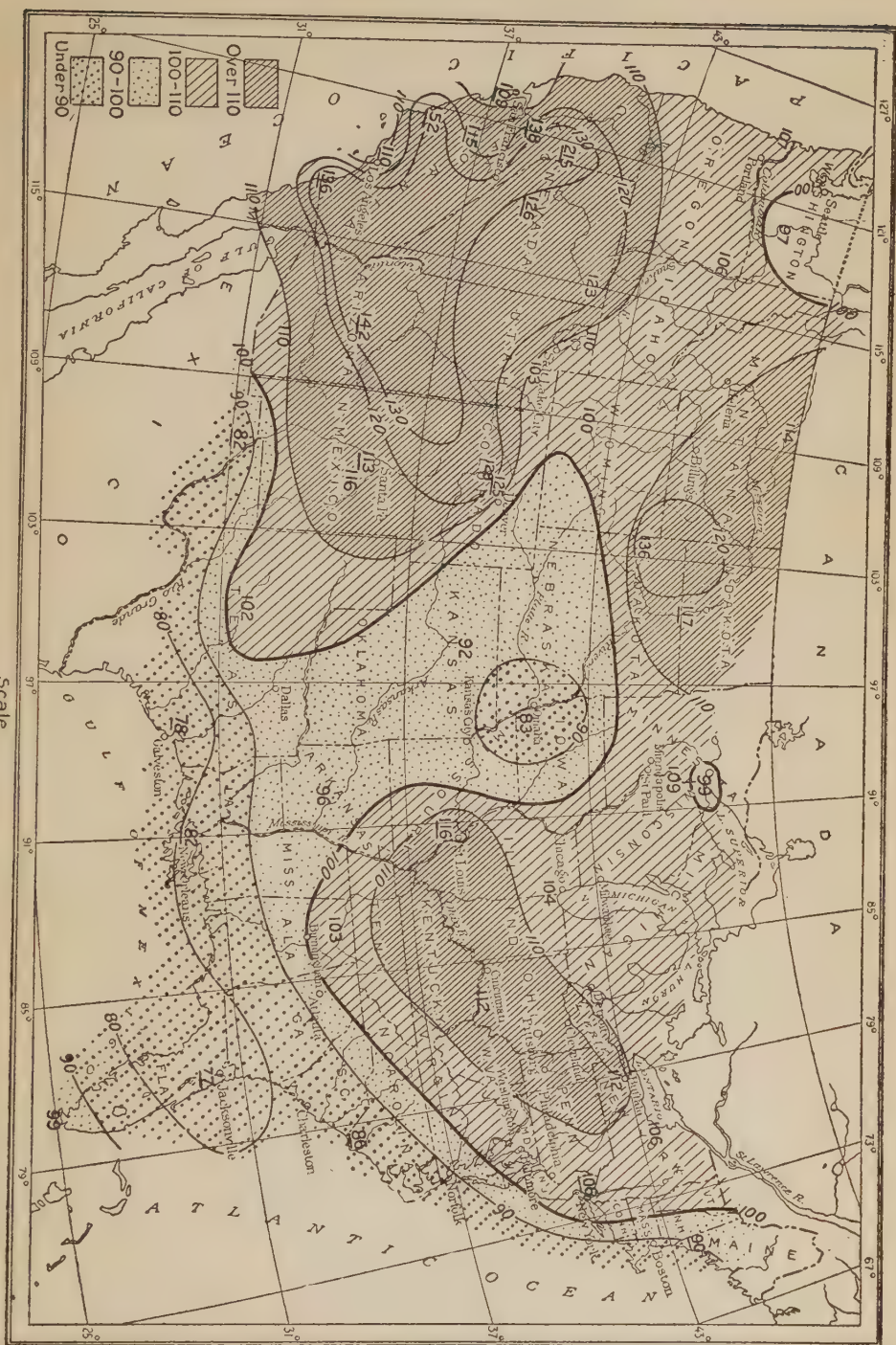


Fig. 3.—Winter rainfall (October to March) in 23 years when Boca had most rainfall compared with 23 years when Boca had least.

If Boca lies in one of the neutral, indeterminate areas, so that it sometimes falls under the influence of a distinctly positive area and sometimes of a negative area, our results may be blurred and inconclusive. If it lies fairly well toward the center of one of the definite areas the results will presumably be clear. In making this study the first step was to add the monthly figures and obtain the rainfall from October to March inclusive at selected stations all over the United States where records were available back to 1871 or 1872. The investigation was restricted to the winter months because Boca has almost no rain in summer, and it seemed unwise to attempt to compare summer rain with that of winter. The two may and often do tend to vary in opposite directions, as at Tucson. Taking, then, the six winter months, the entire 46 years (1871-1916), for which data were available at Boca, were arranged in the order of their rainfall, beginning with the largest and ending with the least. The figures thus arranged were divided first into three groups of 15, 15, and 16 years, A, B, and C in Table 9, and again into two groups of 23 years each (I and II in Table 9). Each group was added and averaged. The rainfall at the other stations was arranged by years in the same order and in the same groups as the Boca rainfall, without regard to whether the amount of rain was large or small. The results appear in Table 9 and figure 3. In the figure the numbers indicate the rainfall of the group of 23 years having most rain at Boca expressed as a percentage of the rainfall of the 23 years having least rain at Boca. Thus 112 at Buffalo means that during the 23 maximum years at Boca the rainfall at Buffalo averaged 20.04 inches for the six winter months, and this is 112 per cent of 17.94 which was the average rainfall at Buffalo during the 23 years with least rainfall at Boca. Where the numbers in figure 3 are underlined it means that when the 46 years are divided into three groups there is a regular gradation. For example at Pembina, North Dakota, the averages for the three groups are 6.29, 6.17, and 4.32; at Jacksonville, Florida, they run the other way and are 15.89 when Boca had most rain, 19.68 during Boca's intermediate years, and 21.95 when Boca was least rainy.

The most interesting feature of figure 3 is its systematic character. The west, especially the southwest, and the north to a less degree are what may be called positive areas. Their winter rainfall tends more or less systematically to increase with that of Boca, and to diminish when it falls off. The center, east, and especially the south display the opposite character. The regularity with which the coastal stations from El Paso along the Gulf of Mexico and up the Atlantic coast not only show percentages well below 100, but also are underlined, shows that we are dealing with a systematic phenomenon. It may be that the use of some other station or of a group of stations instead of Boca would bring out this contrast between the southwest and the southeast still more clearly, but the general fact is obvious. So far as winter rainfall is concerned, a high rainfall at Boca and in the region of the Big Trees is correlated with low rainfall along the coast of the southeastern part of the United States. Presumably the same has been, more or less, true throughout historic times, so that we may infer the approximate winter climate of the southeastern as well as the southwestern part of the United States at any time during the past two or three thousand years by means of the curve of the Big Trees.

Here we must terminate this part of our investigation. We have seen that the mathematical evidence of an intimate relation between the growth

of the sequoias in any given year and the precipitation and temperature at neighboring stations during the few preceding years is too strong to leave much question as to the reliability of the curve of the Big Trees as a measure of climate. We have likewise seen that the positive and negative effects of temperature almost neutralize one another. Hence we have been forced to con-

TABLE 9.—Average winter rainfall in inches for 15 or 16-year periods, and for 23-year periods Oct.-Mar. 1870-1915.¹

	Averages for three groups of 15 or 16 years.			Averages for two groups of 23 years.		
	A	B	C	I	II	I in % of II.
Boca, Nev.....	27.89	16.92	9.91	24.66	11.46	215
Sacramento, Calif.....	18.33	16.86	13.58	18.80	13.59	138
Denver, Colo.....	4.91	4.23	3.56	4.68	3.76	125
La Crosse, Wis.....	9.84	8.65	9.00	9.55	8.72	109
Cincinnati, Ohio.....	19.20	20.27	16.82	19.75	17.69	112
Santa Fé, N. Mex.....	5.38	4.80	3.97	4.80	4.23	113
Fort Union, N. Mex.....	3.73	4.23	3.36	4.23	3.65	116
Las Animas, Colo.....	3.00	2.43	2.61	2.43	1.89	128
Salt Lake City, Utah.....	9.72	8.65	8.90	8.65	8.39	103
Fernley, Nev.....	3.72	3.04	2.24	3.04	2.40	126
Los Angeles, Calif.....	16.83	13.09	12.07	13.09	11.84	110
San Diego, Calif.....	10.17	9.56	6.65	9.56	7.05	136
San Luis Obispo, Calif.....	23.97	18.02	15.79	23.06	15.29	152
San Francisco, Calif.....	22.29	18.76	17.08	21.74	19.91	109
Modesto, Calif.....	11.27	8.45	7.37	8.45	7.30	115
Astoria, Ore.....	60.41	62.87	57.91	62.87	58.85	107
Walla Walla, Wash.....	11.18	10.61	11.14	10.83	11.13	97
Pembina, N. Dak.....	6.29	6.17	4.32	6.17	5.30	116
Independence, Kans.....	12.73	12.29	13.86	12.44	13.49	92
New Orleans, La.....	20.63	25.36	29.60	22.81	27.77	82
St. Louis, Mo.....	16.85	16.09	15.00	17.17	14.75	116
Logan, Iowa.....	8.32	9.29	9.01	8.29	9.39	83
Duluth, Minn.....	8.83	9.21	8.32	8.75	8.83	99
Pemecatur, Ala.....	26.06	26.83	25.41	26.48	25.68	103
Jacksonville, Fla.....	15.89	19.68	21.94	16.73	21.73	77
Key West, Fla.....	15.44	13.91	15.53	14.86	15.06	99
Wilmington, N. C.....	16.63	18.64	21.95	17.68	20.54	86
Buffalo, N. Y.....	19.34	20.40	17.34	20.04	17.94	112
New York City.....	21.78	21.66	20.41	21.89	20.64	106
Wells, Nev.....	6.23	6.71	6.29	7.10	5.77	123
Corinne, Utah.....	7.64	6.54	7.36	7.56	6.85	110
Little Rock, Ark.....	24.58	22.64	26.45	24.07	24.97	96
Chicago, Ill.....	12.71	14.95	12.99	13.85	13.24	104
Washington, D. C.....	17.79	19.98	19.35	18.74	19.35	97
Oswego, N. Y.....	18.64	20.98	16.68	19.27	18.18	106
Lander, Wyo.....	5.02	5.89	5.47	5.34	5.36	100
Portland, Me.....	20.96	22.42	22.88	21.43	23.83	90
Havre, Mont.....	3.86	3.68	3.42	3.88	3.41	114
Tucson, Ariz.....	5.14	5.15	5.00	5.20	4.74	110
Prescott, Ariz.....	9.46	9.17	6.99	10.11	7.13	142
El Paso, Tex.....	2.77	3.16	3.41	2.83	3.43	82
Galveston, Tex.....	16.48	19.88	25.34	18.14	23.18	78
Abilene, Tex.....	7.76	7.42	8.98	8.04	7.90	102
Fort Meade, S. Dak.....	5.18	5.46	4.46	5.84	4.30	136
Joseph, Ore.....	10.47	9.73	9.95	10.36	9.75	106

¹ Sequence of years for all corresponds to that of Boca, where the year with heaviest rainfall is placed first, the next heaviest second, and so on. At other stations the years are arranged in the same order regardless of whether the rainfall is large or small.

clude that in the main the long curve of the growth of the sequoias presents a record of variations in precipitation rather than temperature. Another strong relationship has been found between the growth of the California trees and the present climate of Palestine. In both California and Palestine the changes of climate during the past 3,000 years, as inferred from salt lakes, ruins, and other kinds of evidence, agree closely with the evidence of the trees, so that for these two regions the general climatic pulsations during historic times seem fairly clear. In other regions we have found that as one goes westward from Palestine the apparent relationship between the sequoia growth and rainfall is gradually reversed, until at Algiers it looks as if we were beginning to enter an Atlantic area where an inverse relation prevails. Just where the boundary between these two areas is located we can not yet say, nor can we tell how it has moved back and forth in the past. On the other side of the Atlantic a similar change is found, at least in the winter rainfall, with which we have mainly dealt. As one goes eastward and southeastward from the region of the Big Trees the variations in rainfall gradually change in character until on the Gulf and Atlantic coasts they are the inverse of those in the region of the Big Trees. It may be that the inverse area on the Atlantic coast of America continues across the Atlantic and joins the similar area at Algiers, but this still remains to be tested. Likewise the inverse area of winter rains in the Gulf of Mexico may be related to the inverse area of summer rains of which we have found a suggestion at Mexico City. When these various areas are linked up and the nature of other areas is determined elsewhere, we shall perhaps be able to determine the climate of any part of the earth at any time during the last two or three thousand years by means of the curve of the Big Trees.

PART II. INTERPRETATION OF CLIMATIC CHANGES.

INTRODUCTION.

In most respects the three authors represented in this book agree quite closely. Among the main conclusions as to which they are in accord four may be summarized as follows: (1) The progress of knowledge as to post-glacial climates adds continually to our certainty that since the climax of the last glacial epoch important climatic fluctuations have taken place. (2) These fluctuations have continued during the historic era, although there are diverse opinions as to their intensity. (3) Changes of climate in one part of the world take place synchronously with changes in other parts; in climates of the same type the nature of the climatic variations at any given time is similar all over the world, although changes of quite different types may take place in other kinds of climates. (4) In spite of great differences in magnitude, there is no perceptible difference in character between the climatic fluctuations of the main glacial epochs and those of historic times, and even of our own day.

Although agreed on these main points the three authors disagree on certain other points, the chief of which are as follows: (1) Dr. Antevs and I hold different views as to the relative importance of temperature and precipitation, or storminess as I prefer to put it, as factors not only in tree growth but in the genesis of ice-sheets; (2) Professor Jones and Dr. Antevs disagree as to the age of Pyramid and Winnemucca Lakes and as to the reasons for the comparatively fresh character of their waters, while my own opinion differs from that of either of the others.

LOW TEMPERATURE AS A CAUSE OF GLACIATION.

In respect to the relative importance of temperature and precipitation in causing the accumulation of ice, it should be clearly understood that Dr. Antevs and myself agree in thinking that both factors are important. The question is merely whether changes in temperature are the main or motivating cause of variations in the area covered by snow, or whether the fundamental condition of glaciation was a change in the number, severity, and paths of storms with corresponding changes in snowy precipitation and temperature. Dr. Antevs accepts the established view that glacial periods are due primarily to changes in temperature. In this he is unquestionably supported by the great majority of students, especially among those whose line of approach is geological rather than meteorological.

What is the basis of this long established opinion? Is it not founded largely on pure assumption, rather than on the facts of observation? The assumption may be stated as follows: Ice and snow are phenomena of winter and of places with low temperature. Therefore a great expansion of the area covered by ice and snow must indicate lower temperature than at present. Thus far the reasoning can not be gainsaid. But here follows the final conclusion; hence a diminution of the earth's supply of heat must be the initial factor in causing glaciation. For a long time this conclusion seemed so obvious that no one appears to have thought it needed testing. At length, however,

there began to be hints that changes in precipitation and storminess, and in the movements of the air, may be the primary causes of glaciation, while the changes in temperature, which undoubtedly have occurred, may be secondary phenomena resulting from the other changes.

An historic investigation by Penck has generally been accepted, at least by geologists, as proving beyond question that temperature is really the fundamental factor, and that increased precipitation during the glacial period, if such occurred, was of minor importance. From a study of the upper limits of modern glaciers compared with the traces of ancient glaciation Penck demonstrated that in the Alps the amount of snowy precipitation above the present snowline can not have been greater than at present, even at the height of glaciation, and may have been less. The obvious inference is that in that region, at least, glaciation was due merely to a lowering of the temperature and not to increased snowfall. Similar evidence has been reported from the Tian Shan and Caucasus. So far as I am aware, this is the only type of *direct, observational* evidence ever adduced as proof that temperature is the fundamental factor in glaciation. Of course no serious student of the subject doubts that the temperature during the height of the glacial period was appreciably lower than now, but that is quite different from saying that a drop in temperature was the initial step toward glaciation.

TWO METHODS OF TESTING GLACIAL HYPOTHESES.

There are at least two main ways of testing the matter. One is by reconstructing the climate of glacial times as well as possible, and then drawing *a priori* deductions as to how such a climate could have arisen. The other is to reconstruct the climate of the past, and then to study the climate of the present in order to discover what occurrences now give rise to conditions such as appear to have prevailed in the past. The difference between these two methods is highly important. The first method is valid only if we are sure that glacial periods have arisen because of some cause which is not now acting, or which is now acting in such a mild fashion that its effects can not be detected observationally. Under any other conditions the second method is the only one that can give decisive results. Formerly there was good reason for the first method, for geologists supposed that glaciation occurred so slowly that the period covered by accurate meteorological observations is too short to give evidence of changes, even if any are now taking place. In general, however, it was assumed that the glacial period ended at a definite time in the past, and that its cause is not now acting. In recent years such studies as those of De Geer and Antevis on glacial recession as measured by varves, and those of Taylor on the great number of sub-equally spaced moraines which mark the recession of the ice from New York State far into Canada, have greatly weakened this view. So, too, have studies of historic changes of climate. In fact a great body of evidence seems rapidly to be convincing the world that there is no difference in quality between the climatic changes of glacial periods on the one hand, and those of the post-glacial epoch, of historic times, and even of the brief climatic cycles of our day on the other hand. If this is true, one of the most effective methods of studying the causes of glaciation is to investigate the conditions which now prevail at times and places where there is a heavy and prolonged cover of snow.

SNOWFALL OF THE HIGH ALPS.

A concrete application of this method is found in certain observations of Maurer.¹ During the very snowy winter of 1906-7 he noted that the very high Alps, over 3,000 meters in altitude, "had only a little snow to show," whereas at lower levels there was much more than the usual amount. If this condition is widespread, and theoretically there is reason to think that it may be, it destroys at a blow the whole of Penck's argument. Of course further data are needed. The important point, however, is that in the very place where Penck thought that lack of snow at high levels indicated low temperature without any increase of precipitation, Maurer finds that in the only case on record, so far as I am aware, a lack of snow at those same levels was accompanied by unusually heavy snow at lower levels. In other words an unusual degree of storminess gave rise to exactly the conditions which cause the snow to lie late in the spring, and which depress the snowline and bring the ends of the glaciers to lower levels. This does not impair the value of Penck's careful study; it merely suggests that he drew an unwarranted conclusion because of lack of knowledge of what happens to-day as well as in the past. His facts show that during the glacial period there prevailed in the high Alps the same relative dearth of snow which now prevails, sometimes at least, when the snowfall at lower levels is unusually heavy. Thus what has long been supposed to be positive proof that glaciation was due to the lowering of the earth's temperature turns out to have quite as much weight in proving that glaciation was due to increased storminess. Neither conclusion is warranted until we have looked further into the relation between temperature and precipitation during our present climatic cycles.

TEMPERATURE AND THE SNOWLINE.

In general it appears that variations in temperature bear no constant or uniform relation to variations in precipitation. The truth of this statement may be judged from the following facts taken from Hann.² The snowline on the south side of the Himalayas lies at an altitude of about 4,900 meters; farther north where the temperature is *lower* and the precipitation much less, it lies at about 5,600 meters at Leh and at 6,100 at Lake Pangong. On the slopes of Kilimanjaro in latitude 3.5 S. the snowline on the moist south and west sides lies at 4,600 meters, whereas on the dry north and east it rises to 5,500. In both these cases, and in many others, the snowline lies low where there is abundant precipitation, even though the temperature is relatively high; whereas it lies high where the precipitation is scanty, even though the temperature is low. Other evidence to this same effect is the temperature at which the snowline occurs. Near Quito, in the moist and uniform climate of the equatorial Andes, the snowline lies at an altitude where the mean annual temperature is 3° C. above freezing; on the dry Tibetan side of the Himalayas the corresponding figure is -4° to -5°; in the cold region of Nova Zembla, where the total precipitation is slight, -10° to -11°; and in north-eastern Siberia -17°, or less. In fact, in this last region there is no snowline up to an altitude of 600 meters, although the annual mean temperature must

¹ J. Maurer, *Über die Strahlung einer freien Schneefläche in absoluten Masse und die Schneefälle in Winter 1906-7 der Schweiz*, Meteor. Zeit. vol. 24, 1907, pp. 294-300.

² J. Hann, *Klimatologie*, 3d ed., Stuttgart, 1908.

be well below -17°C . Similar variations occur in the mean annual temperature at the lower ends of glaciers. In New Zealand and British Columbia the larger glaciers end where the temperature averages 10°C .; in southern Chile, 8.4° ; but in eastern Siberia, on the south side of Munku-Sardyk, -10° . In Alaska, along the coast where the precipitation is abundant and the summer temperature low, the glaciers near Mount Saint Elias break off in the ocean with ice walls 100 meters high; in the interior, in the same latitude but with less precipitation and warmer summers, no glaciers are found on the sides of the mountains even at an altitude of 1,200 to 1,500 meters. This is true as far north as the Arctic Circle. Even when the fullest allowance is made for topography, it seems that neither a low annual temperature nor a low winter temperature is the main factor in depressing the snowline and bringing glaciers to low levels. The two things that are chiefly effective are abundant snowy precipitation in winter and cool summers.

COMPARATIVE INDEPENDENCE OF ANNUAL VARIATIONS IN TEMPERATURE AND PRECIPITATION.

Let us next inquire into the relation between variations in precipitation and temperature from year to year in the same place. In general there seems to be no constant or intimate relation between the two. For example, at Berlin from 1866 to 1905 the 10 most rainy years and the 10 least rainy showed the following conditions:¹

	Average annual precipitation.	Average annual temperature.
10 most rainy years.....	<i>mm.</i> 670	$^{\circ}\text{C}$. 9.15
10 least rainy years.....	483	9.35

In other words, the most rainy years had 39 per cent more rain than the others, and their temperature was only 0.2° lower. In Jerusalem, during the 25 years for which data were at hand when the present investigation was made, the conditions were as follows:

	Average annual precipitation.	Average annual temperature.
13 most rainy years.....	<i>in.</i> 34.1	$^{\circ}\text{F}$. 62.04
12 least rainy years.....	24.4	62.44

In this case a difference of rainfall similar to that at Berlin was accompanied by a similar difference in temperature, but in the opposite direction.

Another interesting example is a comparison of two ten-year periods in the Gulf States. The cities of Vicksburg, Shreveport, Galveston, and New

¹ Ellsworth Huntington, *The solar hypothesis of climatic changes*, Bull. Geol. Soc. Amer., vol. 25, 1914.

Orleans mark the corners of a quadrilateral some 400 miles on a side. Here are their average data.¹

	Average annual precipitation.	Average annual temperature.
	<i>in.</i>	<i>° F.</i>
10 years 1875-1884.....	59.4	67.36
10 years 1890-1899.....	42.4	66.94

Here we have a long continued and large difference of precipitation accompanied by an insignificant difference of temperature. The cooler years had the lower precipitation, as at Berlin.

Another method of testing the relation of temperature and precipitation has already been described. At Sacramento, by means of correlation coefficients, we found no relation between the two. Examples might be multiplied indefinitely. They would make it clear that large variations of precipitation may take place without appreciable variations of mean temperature. Heavy precipitation may occur with either relatively high or relatively low temperature. It depends upon local conditions of wind, altitude, and the relative position of land and water. This seems to make it fairly clear that the storms which give rise to precipitation act more or less independently of the local temperature.

EFFECT OF TEMPERATURE ON SNOWFALL.

Let us look more intimately at the relation between snow and temperature. It is generally supposed that winters with much snow tend to be warmer than those with little. This idea arises partly from the fact that in all parts of the world by far the greater part of the snowy precipitation takes place at temperatures within a few degrees of the freezing point. In the Erzgebirge, for example, Berthold² found that at an altitude of 500 meters 40 per cent of all the snow falls at temperatures from -1°C. to $+1^{\circ}\text{C.}$ This happens in spite of the fact that much of the winter has temperatures much lower than this. During the period of his study, the precipitation at temperatures above freezing actually amounted to 41 per cent of the total. The heaviest individual snowfalls took place at temperatures near the freezing point. Similar conditions prevail all over the world. The relatively high temperature at which snow usually falls is connected with the fact that snowfall generally occurs when a cyclonic storm brings a supply of warm air from lower latitudes.

In contrast with the low barometric pressure and relatively warm air at times when snow falls abundantly is the fact that during winters with little snow, in middle or high latitudes, the continental type of atmospheric pressure tends to prevail, that is, high pressure over a central area, and diminishing pressure toward the coasts. The air in the high pressure center is clear, radiation is rapid, and the temperature falls to low levels. Thus cold winds prevailingly blow outward from the high area and chill the surrounding regions.

¹ A. J. Henry, *Secular variation of precipitation in the United States*, Bull. Amer. Geog. Soc., vol. 46, pp. 192-201, 1914.

² Berthold, *Meteor. Zeit.* vol. 23, 1888, p. 30.

This contrast between winters with much and little snow prevails in both hemispheres, as may be seen from Clayton's data in *World Weather*.

Cold regions as well as cold seasons are characterized by relatively little snow. It is well known that the coldest parts of the earth, such as the Yakutsk district in Siberia, have little snow, and were not glaciated during the last glacial epoch. Central Montana is much colder in winter than Central New York or Maine, but the period when it is covered with snow is usually much shorter. The reason is largely that less snow falls in Montana than in the other places. It must not be forgotten that even in cold weather a considerable amount of snow disappears by evaporation. Henry¹ has shown that in the coldest, least windy weather in the high Sierra, the evaporation from a snowy surface under a clear sky amounts to three-fourths of an inch per day. Thus, unless storms come at frequent intervals, a cover of 5 or 6 inches of snow, such as is common in regions like Montana, is likely to disappear within a few weeks.

EFFECT OF A SNOW COVER UPON TEMPERATURE.

Although low temperature always tends to lessen the snowfall, it must be clearly understood that sufficient snow to cover the ground for some days is a pre-requisite to the lowest temperatures. This important principle was first set forth by Woeikof² and has been abundantly confirmed by Köppen² and others. Nevertheless, it is still very largely overlooked, especially by geologists. As Köppen puts it, "It seems, therefore, that the continental type of [high] pressure brings cold with it only in case of being preceded by a wide-spread cover of snow; in all other cases, even in winter, it is relatively warm." Again, to quote Woeikof, "in west and south Europe, where the ground is not commonly covered with snow, this circumstance is well known, and people always expect the greatest cold when snow has fallen. For example, the high degree of cold in December 1860 in Great Britain followed immediately after heavy snow."

TABLE 10.—*Excess temperature on snow-free compared with snow-covered days at Upsala. Absolute minimum at Upsala during 14 years, 1874-1888.*

	Excess in mean temperature.	Excess in mean minimum temperature.	Excess in mean maximum temperature.
	° C.	° C.	° C.
November.....	4.7	8.9	5.3
December.....	5.1	6.9	3.9
January.....	6.0	7.8	5.2
February.....	5.1	8.2	4.6
March.....	5.2	7.8	5.1
Average.....	5.2	7.9	4.8

¹ A. J. Henry, *Geog. Rev.*, vol. 2, p. 61, 1916.

² A. Woeikof, *Der Einfluss einer Schneedecke auf Boden, Klima und Wetter*, *Geog. Abhandl.*, vol. 3., part 3, 1889.

W. Köppen, *Verhältnis von Frost, Schneedecke und Luftdruck in Norddeutschland im winter 1906-7*, *Meteor. Zeit.*, vol. 24, pp. 323-5, 1907.

W. J. van Weber and W. Köppen, *Die Isobarentypen des Nordatlantische Ozeans und Westeuropas*, *Archiv der Deutsche Seewarte*, 1895.

Table 10 from Woeikof shows how systematically the days with a cover of snow during 14 years at Upsala in Sweden averaged colder than the days when there was no snow on the ground. The figures show the average amount by which the temperature of the snow-free days exceeded that of those with snow.

The difference between days with and without snow would be still greater were it not that the days when snow was on the ground averaged slightly more cloudy than the others. At Upsala in winter the clear days are cooler than the cloudy as appears from the following figures for the months of December, January, and February. On clear days the cooling effect of snow is also more noteworthy.

	Clear.	Partly cloudy.	Cloudy.
	° C.	° C.	° C.
Days with snow cover.....	-9.9	-6.7	-4.9
Days without snow cover.....	-1.7	-0.1	-0.2

The critical reader may say that the low temperature of days with snow on the ground is due partly to the fact that such days are especially frequent in midwinter, while snow-free days prevail during the earlier and later parts of the cold season when the temperature is not so low. But Woeikof¹ divides the entire period from November 2 to March 31 during his 14 years into 34 five-day periods, i. e., Nov. 2-6, Nov. 7-11, etc. "In none of the 34," he says, "is there any exception to the preceding rule that the mean temperature, and likewise the maxima and minima, are lower when snow lies on the ground."

It will be noticed that in Table 10, where Woeikof's results for Upsala are given by months, the average minimum temperature of days when snow lay on the ground is 7.9° C. lower than the corresponding figure for days without snow. If we take the absolute minima, the differences between days with and without a cover of snow are still greater, as appears below:

Absolute minimum at Upsala during 14 years, 1874-1888.

	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.
	° C.	° C.	° C.	° C.	° C.	° C.
Ground covered with snow.....	-23.5	-26.1	-39.5	-28.9	-26.9	-22.4
Ground free from snow.....	-15.3	-16.8	-11.8	-14.8	-13.4	-10.3
Difference.....	8.2	9.3	27.7	14.1	13.5	12.1

A noteworthy fact about this table is that the same type of contrast prevails in November or April when the ground is covered with snow only a fourth or a fifth of the time, and in January when it is covered more than three fourths of the time. The differences are not due to differing barometric conditions, for Woeikof shows that when the averages of many years are taken, the periods of high pressure, the continental type, show the same kind of contrast between

¹ A. Woeikof, *Der Einfluss einer Schneedecke auf Boden, Klima und Wetter*, Geog. Abhandl., vol. 3, part 3, 1889.

snow-covered and snow-free days as do days of other barometric types. The fact seems to be that at Upsala it is practically impossible for the temperature to sink much below -17°C. , no matter what kind of barometric pressure may prevail or how clear the skies may be, unless the ground is snow-covered.

Woeikof is not content with mere averages. He cites many convincing individual examples of the way in which a cover of snow lowers the temperature. One must suffice.

At Petro-Alexandrovsk [in Transcaspia between Merv and the Sea of Aral] on January 25-26, 1877, there fell 7.3 mm. of snow with a temperature somewhat below 0°C. Till the end of the month the ground was covered with a thin cover of snow. During this time the temperature sank to -25.5°C. on the morning of the 29th and -26.5° on the 30th. The wind was northeast, but not strong, being not over 7 meters per second on the 26th to 28th, while on the 29th it was only 4 meters per second.

Farther to the north and northeast, in the Khirghiz Steppes and the southern part of West Siberia, it was only a little colder at this time than at Petro-Alexandrovsk, about $1-4^{\circ}$ at Omsk [latitude 55°] and Irgis [lat. 49°], and somewhat warmer in Semipalatinsk on the Irtysh in latitude $50\frac{1}{2}^{\circ}$. Nowhere within a radius of 1,500 kilometers from Petro-Alexandrovsk was the temperature on January 28-30 lower than -35°C. The cooling in the latter place was extraordinary for the latitude [$41\frac{1}{4}\text{ N.}$], and must in large part have occurred right then and there.

Woeikof contrasts this with another occasion, December 1877, when the temperature at Petro-Alexandrovsk fell to -33.1° . This time there was no snow on the ground, but a northeast wind was blowing at least 50 per cent more rapidly than on the other occasion. The low temperature evidently was brought by the wind, for at Barnaul, Tomsk, and Semipalatinsk there were temperatures below -50°C. about 3 days earlier. In this case the temperature had risen about 20° while the air was moving 10° southward. That is the normal condition. In the preceding January, however, although the air moved southward more slowly than in December, and hence had more time in which to become warm, it scarcely changed its temperature. As Woeikof puts it:

No other explanation of this circumstance is indeed possible except that in January 1877, the cold [in the Merv region] developed in large part from radiation then and there, especially by reason of the snow cover. In December, on the other hand, when there was no snow, the cold was brought directly by the north and northeast wind, and thereby the air warmed itself $15-20^{\circ}$ in travelling 1,000 kilometers.

HOW A COVER OF SNOW LOWERS THE TEMPERATURE.

In the preceding paragraphs we have been dealing with two causes of low temperature which may act together or independently. One is a continental location in fairly high latitudes, which in winter is favorable to low temperature. The other is a cover of snow. The fact which needs emphasis is that, contrary to the common opinion, mere continentality is by no means enough to produce the lowest temperatures; a cover of snow is also necessary. Snow promotes low atmospheric temperature in three chief ways. (1) Since snow is a poor conductor of heat, it is warmed relatively little by radiation from the earth below it. For example, at Upsala., Jansson and Westman¹ found that

¹ M. Jansson and J. Westman, *Quelques recherches sur la couverture de neige*, Bull. Geol. Inst. Upsala, vol. 2, part 10, pp. 234-260, 1901.

in February and March 1902, the mean temperature of the air and that of the snow at various depths was as follows:

	Feb.	Mar.
	° C.	° C.
Air, hourly average.....	-5.9	-3.5
Snow, depth of 5 cm.....	-3.5	-1.4
Snow, depth of 10 cm.....	-3.9	-1.7
Snow, depth of 15 cm.....	-3.4	-1.4
Snow, depth of 20 cm.....	-3.1	-1.3
Soil at surface.....	-1.1	-0.5

The presence of the snow prevents the soil from cooling rapidly and causes it to retain a certain amount of heat from the preceding season. If there were no snow, this heat would be available to warm the air. (2) The snow cools off by radiation so that it becomes colder and colder toward the top, as appears above. The slight irregularity in the preceding figures at a depth of 5 cm. is due to the downward penetration of the heat of the sun. The general decline in temperature from the surface of the soil to the top of the snow, on the other hand, is due to the radiation of heat by the snow itself. Because of such radiation the minimum temperature of the surface of the snow is systematically lower than the minimum temperature of the air. At Upsala, in 1902, Jansson and Westman found that the minimum for the snow averaged below that of the air by the following amounts, February, 4.1° C.; March, 2.5°; and April, 3.6°. They quote Juhlin ¹ to the effect that at Upsala in 1887 and 1888, during clear, quiet nights, the temperature of the surface of the snow averaged 4° C. cooler than that of the air at a height of 1.4 meters above it. Obviously the radiation from the snow leaves the snow so cold that it acts as a means of cooling the air most of the time. (3) A third reason why snowy areas have relatively low temperatures is the high reflecting power of snow, whereby a large part of the sun's radiation is sent back into space. Thus by its blanketing effect, by radiation, and by reflection a cover of snow leads to low temperature of the air.

HOW A COVER OF SNOW HELPS TO CAUSE MORE SNOW.

Although the low temperature and consequent high barometric pressure induced by a cover of snow tend to diminish the amount of precipitation, the snow increases the likelihood that the precipitation will take the form of snow rather than rain, provided a storm succeeds in forcing its way into the snowy area. This is because, even when warm winds are brought by cyclonic disturbances, the melting of the snow holds the temperature down to a low level. Here are some figures from Johansson ² showing the temperatures at Kayana and Bogskär in Finland during the month of February for 15 years. The days at each place are divided into three groups according to temperature. The noteworthy fact is the uniformity of the maximum temperature. It

¹ Julius Juhlin, *Sur la température nocturne de l'air à différentes hauteurs*, Nova Acta Reg. Soc., Upsala, 1890.

² Osc. V. Johansson, *Dampfende Wirkungen des Schnees und Eises auf die Luft-temperatur*, Oversigt af Finska Vetenskaps-Societetens Förhandlingar LV., 1912-13 Afd. A., No. 11.

varies only 5° C., whereas the mean temperature varies 14.3° and the minimum 23°. For our present purpose the important point is that so long as there is a cover of snow, the chances of further snow are thereby increased, *provided there are storms.*

	Kayana.			Bogskär.		
	I. Cold days.	II. Medium days.	III. Warm days.	I. Cold days.	II. Medium days.	III. Warm days.
Mean temperature.....	° C. -14.1	° C. -10.6	° C. - 5.3	° C. - 5.4	° C. - 2.3	° C. -0.2
Maximum temperature	0	+ 3	+ 4	+ 4	+ 5	+5
Minimum temperature.....	-30	-23	-21	-19	-10	-7

Even though the storms bring warm winds which would otherwise produce rain, the snow cools them almost to the freezing point, thus maintaining the temperature at approximately the level where the conditions are most favorable for heavy snow.

RELATION OF STORMS TO TEMPERATURE.

In the preceding discussion we have seen again and again that the two essentials for heavy snowfall are temperatures fairly near freezing and cyclonic storms. Let us study the effect of storms upon temperature more carefully. An ordinary cyclonic storm in middle latitudes, as is well known, is preceded by winds which are relatively warm at most seasons. It is followed by winds from other quarters which are generally cool and often very cold. Many storms begin with snow and end with rain. In New Haven, according to Tarr, the local forecaster, such storms are twice as numerous as those that begin with rain and end with snow. But when snow already lies on the ground at the beginning of a storm, the later precipitation of the storm is likely to take the form of snow, even though rain falls at the beginning. The more severe the storm, as a rule, the greater the contrasts in temperature before and after it; the stronger the upward movement of the warm air, the greater the likelihood of snow, and the greater the probability that the inflowing cold air at the end of the storm will have a temperature low enough to allow the snow to remain on the ground unmelted. Within the limits formerly covered by ice sheets, a sufficiently severe storm may cause snow to cover the ground during practically any month of the year. As soon as such a cover is formed it begins to lower the temperature of the air by its blanketing effect on the soil, by its own radiation, and by its reflection of the sun's radiation. In addition to this, cyclonic storms appear to lower the temperature in at least three other ways. First, in relatively low latitudes and in warm weather elsewhere, the cloudiness of the storms shuts out the sun's heat, and may thus exert a cooling effect which overbalances the warming effect due to shutting in the heat radiated from the earth. Second, the fall of rain in similar warm regions often has a pronounced cooling effect as Clayton clearly shows in *World Weather*. The atmospheric moisture, to be sure, gives up its latent

heat when it condenses into raindrops, and thereby warms the upper air. Nevertheless, the rain is often many degrees cooler than the air near the earth's surface. Since it is warmed only a little during its descent, it exerts an easily detectable cooling effect. Third, as stated in *Earth and Sun*, every cyclonic storm is characterized by the upward movement of air in its center. When this air comes from relatively low latitudes and is replaced by cool air from higher latitudes, as is regularly the case in the vast majority of storms, the uplifting of the warm air removes considerable quantities of heat. This air doubtless warms the upper parts of the air, but it is lost to the parts near the earth's surface and thereby tends to lower the temperature. Thus in at least four different ways cyclonic storms tend to lower the mean temperature of the air near the earth's surface, namely (1) by creating a cover of snow, (2) by cloudiness under certain conditions, (3) by causing the fall of cool rain, and (4) by forcing large bodies of warm air to high levels. The cooling effect of cloudiness under certain circumstances is perhaps fully offset by the warming effect when the clouds serve as a blanket to keep in the earth's heat. The other three ways of cooling the lower air seem to have nothing to offset them so far as the lower parts of the air are concerned, although in the upper air the case is quite different. These facts as to the cooling of the air by cyclonic storms are especially significant in view of the apparent absence of any evidence that low temperature increases the precipitation.

Our results may be summed up thus:

There is no evidence that a lowering of the earth's mean temperature would increase the earth's snowy precipitation. On the contrary, there is considerable evidence that it would diminish such precipitation. There seems as yet to be no evidence to prove whether the lowering of the snowline by low temperature is greater or less than the recession of the snowline due to the diminution of snowy precipitation which must apparently arise from any such lowering of temperature. Opposed to this is a large body of evidence which shows that cyclonic storms not only produce the greater part of the earth's snowfall, but through that same snowfall, as well as in other ways, tend to lower the earth's mean temperature.

SNOWFALL AND STORMS IN NEW ENGLAND.

As the next step in our investigation I propose to summarize an article by C. F. Brooks on *New England Snowfall*.¹ He begins with certain observations which confirm the results that we have already set forth. He states:

The records of Blue Hill Observatory near Boston show that, in general, the greater the number of days with snow on the ground in a winter month (December to March) the lower is the temperature relative to the mean. Furthermore, in months with long-enduring snow cover there are the greatest inversions of temperature between the top of the hill and the valley station 600 feet below. With an average depth of 26 inches of snow on the ground on February 15, 1899, simultaneous temperatures at the top of the hill and in the valley were 8° F. and -20° F. respectively, the greatest difference recorded there up to that time.

Brooks goes on to discuss the conditions under which unusually heavy snowfall occurs in New England. Three sets of conditions are especially

¹ *Monthly Weather Review*, vol. 45, pp. 271-285, 1917.

favorable. (1) A cyclone over the Great Lakes and another off the South Atlantic coast, uniting south of New England and moving northeast. "When a previously formed snow cover is present, the cold air and consequent tendency for the anticyclone to stick over New England serve to intensify and delay the cyclone," thus giving it time to cause unusually heavy precipitation. Such precipitation, Brooks shows, depends more upon the length of time that snow continues to fall than upon the rate of fall. (2) Another set of conditions favorable for heavy snowfall in New England is "a single cyclone which fights its way up the coast against the southward circulation on the east side of a great anticyclone lying dominant over the intensely cold, snow covered ground." Here again we have the combination which the European authorities emphasize, namely, on the one hand, low temperature and extreme anticyclonic conditions under the influence of the snow left by a previous cyclonic disturbance; and on the other hand, a new cyclonic disturbance strong enough to push its way into the high pressure area or at least to maintain itself on the border. Such a disturbance raises the temperature along its front, but because of the previous snow cover can not give rise to temperatures much above freezing. Thus it creates conditions ideal for heavy snowfall. (3) The third set of favorable conditions comprises any combination which results in the passage of a strong cyclone immediately south of or northward through New England while an anticyclone on the northeast or north is in the way. "Snowy winters, while sometimes taking their character from a single storm, are generally the result of the passage of a number of cyclones south of or through New England."

THE FUNCTION OF STORMS IN GLACIATION.

Without going further into details, the evidence seems to indicate that conditions like those of the glacial period, although of course on a mild scale, now occur when cyclonic storms are unusually vigorous and numerous. Under such conditions large areas are covered with snow early in the season. That leads to an unusual development of continental areas of high pressure. If the storm-making forces are weak, further precipitation may be checked until the snow disappears. If the storm-making forces are strong, and if something impells them to push northward, as described by Brooks, the conditions for heavy snowfall are realized, and the snowfall may be repeated time after time as long as the storms are vigorous and the winter remains cold. Such conditions seem to give almost precisely the combination required to produce glaciation, namely, unusually low temperature, unusually heavy precipitation, and late springs with stormy, cloudy, cool summers.

Cyclonic storms are perhaps the most variable of the main climatic elements. In the regions that were the chief centers of Pleistocene glaciation, and along the margins of the present main glacial areas in Greenland and Antarctica, this is especially true. Maps of four successive solar cycles prepared by Kullmer¹ all agree in showing that, when sunspots are numerous, there is a pronounced tendency for the storms of North America to increase in number and to be concentrated in a band extending in a broad arc from British Columbia through the Great Lakes region, down the St. Lawrence to New-

¹ For details see Huntington and Visser, *Climatic changes*, 1922; and especially Ellsworth Huntington: *Earth and Sun*, 1923.

foundland, and thence across the Atlantic in a course not yet charted. In Europe there are signs of a similar tendency, but the records of storm tracks are very incomplete.¹ In the southern hemisphere a great band of storms extends completely around Antarctica, but as yet we have no data as to what happens to it when sunspots are numerous. In each of the three glaciated continents the main area of storminess lies roughly parallel to the border of the ancient ice sheets. In North America at times of great solar activity the zone of greatest storminess tends to move toward the old center of glaciation, and there are hints of the same thing in Europe. Such being the case there seems to be good ground for believing that glacial periods and all the other climatic cycles of minor degree down to the present solar cycles are more likely to owe their origin to variations in the number, intensity, and paths of cyclonic storms than to variations in temperature. As to what causes the variations in storminess there is much diversity of opinion. In *Earth and Sun* and in *Climatic Changes* I have discussed the evidence which has forced me to conclude that the climatic cycles are due primarily to variations in the activity of the sun's atmosphere. The solar activity appears to influence the earth's atmosphere through a combination of agencies in which temperature may play the chief part, but in which electrical conditions may interpose certain tendencies which are especially important in increasing the amount of storminess.

ANOMALY OF PYRAMID AND WINNEMUCCA LAKES.

Let us now turn to the second of the main divergencies in the views of the authors of this book. Professor Jones holds that the low degree of salinity of Pyramid and Winnemucca Lakes indicates that they must have been desiccated or else have overflowed within a few thousand years. The lack of any evidence of overflow from Pyramid to the Smoke Creek Basin since the last expansion of Lahontan seems to exclude the possibility that the lakes were freshened by overflow. Hence Professor Jones concludes that Lake Lahontan "had its beginning between 2000 and 4000 years ago, and reached its maximum depth and extent about 1000 years ago." Dr. Antevs believes that it is impossible that the Lahontan basin should have compressed into 3000 years, more or less, a series of events which in the Bonneville basin, a little farther east, appear to have taken perhaps twenty times as long. Hence, in spite of the evidence submitted by Professor Jones, Dr. Antevs believes that Pyramid Lake must have overflowed to the north some three or four thousand years ago.

Formerly, as appears in the first two editions of *Civilization and Climate*, but not in the third, I fully shared the opinion of Dr. Antevs. Now I share it in part, but feel that Professor Jones has shown conclusively that the outlet from Pyramid Lake to the Smoke Creek Basin has not carried any appreciable overflow during historic times, although it presumably did so long ago, perhaps, before the last glacial epoch, when the last main expansion of Lahontan was taking place.

The facts which I am about to set forth appear to show the real state of affairs, and to harmonize the divergent views. The main point in which I

¹ Ellsworth Huntington, *The solar hypothesis of climatic changes*, Bull. Geol. Soc. Amer., vol. 25, 1914.

differ from either of the others is in believing that Pyramid Lake was freshened by overflow to Winnemucca, whereas Winnemucca dried up at some time during the historic period and thereby also became fresh.

BIFURCATION OF THE TRUCKEE RIVER.

The reason for this view is graphically shown in the Wadsworth sheet of the topographic map of the United States. It was clearly stated by Russell, in the *Geological History of the Lahontan*:

The most interesting feature to the geologist in the present condition of the Truckee River is its bifurcation shortly before reaching Pyramid Lake. * * * The stream divides so as to deliver a part of its waters to Pyramid Lake and a part to Winnemucca Lake. The branch entering Pyramid Lake [about a mile and a half in length according to the Wadsworth sheet] has the ordinary features of a river winding through an alluvial bottom, and has formed a low-grade delta of broad extent. * * * The waters that are tributary to Winnemucca Lake leave the main stream at nearly a right angle and flow [five or six miles] through a deep narrow channel carved in Lahontan sediments. [At one place the map shows the outlet valley as having a depth of not less than 225 feet, with a width at the top of less than half a mile.] This stream or "slough," when measured in September 1882, had a volume of 2,400 cubic feet per second. From the manner in which the bifurcation takes place it can not be considered as the breaking up of a stream on a delta or an alluvial slope, as in the case of the Carson River after entering the Carson Desert, but must have been originated by the waters overflowing from Pyramid to Winnemucca Lakes, or *vice versa*. (p. 43.)

The only published account known to us of the bifurcation of the Truckee River, so as to supply two lakes, is given by Mr. King (*Geological Exploration of the Fortieth Parallel*, vol. 1, pp. 505-6), who states that "At the time of our visit to this region in 1867, the river bifurcated; one half flowed into Pyramid Lake, and the other through a river 4 or 5 miles long into Winnemucca Lake. At that time the level of Pyramid Lake was 3,890 feet above the sea, and of Winnemucca about 80 feet lower. Later, owing to the disturbance of the balance between influx and evaporation already alluded to as expressing itself in Utah by the rise and expansion of Great Salt Lake, the basin of Pyramid Lake was filled up and a back water overflowed the former region of bifurcation, so that now the surplus waters all go down the channel into Winnemucca Lake, and that basin is rapidly filling." (pp. 63-4.)

Russell goes on with further details as follows:

The differences in elevation between Pyramid and Winnemucca Lakes, as reported by Mr. King, and as determined by the present survey in August 1882, are as follows: In 1867 Pyramid was 80 feet higher than Winnemucca; in 1872 Pyramid was 67 feet higher than Winnemucca; in 1882 Pyramid was 12 feet higher than Winnemucca, as determined by engineer's level; [and in 1890, according to the Wadsworth sheet of the U. S. Geological Survey, the difference had been reduced to 5 feet.]

We know of no accurate means of determining how much each lake individually has varied since 1872, but the decrease in the difference of the levels of the two lakes is certainly due in part to the lowering of the waters of Pyramid Lake, as is indicated by recent tufa deposits and lines of bleached seaweed at an elevation of about 12 feet above the present surface of the lake. From the data now in hand [1885], providing all measurements are correct, it is evident that Winnemucca Lake has risen over 40 feet since 1872, and over 50 since 1867.

The history of the fluctuations of these lakes is supplemented and enlarged by the statements of Mr. George Frazier, who has been familiar with the region since 1862. In his judgment Winnemucca Lake has risen about 40 feet in the last 20 years. In 1862, the branch of the Truckee River that supplies Winnemucca Lake was so low that a person could cross it by stepping from stone to stone, at a point where it is now not less than 25 feet deep. The lake was then confined to the northern extremity of its basin, and the stream reached it after meandering through meadow lands that are now 15 or 20 feet under water. [According to Russell's map, a drop of 60 feet in the level of Winnemucca would cause the waters to retreat 4 miles from the present southern extremity, and less than a mile from the northern. A further drop of 27 feet would bring the level to the lowest point shown by

Russell's soundings, and would cause almost complete desiccation.] At that time the channel of the stream could be traced along the bottom of the lake some distance, and dead cottonwood trees were standing in the water, showing that the lake had previously been much lower. Dead trees standing in Pyramid Lake, some distance from shore, bore similar evidence to the rise of that lake previous to 1862. This lake, however, is thought by Mr. Frazier to be much higher at present than when he first saw it. During the spring and summer of 1868 the Truckee delivered more water than usual, and Pyramid Lake rose 10 or 15 feet. This rise continued throughout the following year, and during these two years Pyramid overflowed into Winnemucca Lake. The water in the "slough" [between the two lakes] at that time was brackish and unfit to drink. In the summer of 1876 all the water in the Truckee emptied into Winnemucca Lake, its outlet into Pyramid Lake having been closed by a gravel bar; but the annual rise of the river the following spring removed the obstruction. These observations, although not of scientific accuracy, are yet of value, and have been confirmed by other people who have been acquainted with these lakes for a number of years.

We may note here that the rise of Pyramid and Winnemucca Lakes during the last 15 or 20 years is synchronous with a similar increase observed in Goose, Horse, and Mono Lakes, California; Walker and Ruby Lakes, Nevada; Great Salt and Rush Lakes, Utah.

It seems to me that this array of facts leaves little question as to the main course of events. Something over a century ago, that is, at the time when the cottonwood trees described by Mr. Frazier began to grow, Winnemucca must have been at least 60 and perhaps 70 feet lower than at present. Its area can scarcely have been more than 50 to 60 per cent as great as now, and may have been less. At the same time Pyramid Lake also appears to have stood lower than at present. Under normal conditions the Truckee River flows directly to Pyramid Lake. Apparently it would never reach Winnemucca at all were it not that sometimes, as in 1868-69, the river fills Pyramid to overflowing, and thus an outlet channel is eroded from that lake to Winnemucca. The river is so delicately balanced between the two lakes, however, that the whole stream may also flow temporarily to Winnemucca, as in 1876, but such a condition can not be permanent, for under such circumstances the smaller lake would quickly be filled and there would be a flow back into Pyramid Lake. Moreover, whenever the lakes are at nearly the same level, the river is bound to flow to Pyramid most of the time or in largest volume, since no stream, in its deltaic portion, will permanently follow a course of 5 or 6 miles when it has at its command an equally open channel having a similar fall in a distance of only a mile or two.

FRESHENING OF PYRAMID LAKE.

The present conditions afford a good key to the past. There can, I believe, be little doubt that the last main expansions of lakes Lahontan and Bonneville culminated at approximately the same time, that is, during and just after the maximum expansion of the last ice sheet. For 30,000 years, more or less, both lakes tended to grow smaller, although both, presumably, were subject to great fluctuations so that they sometimes expanded and again contracted. Nevertheless, the net result was a diminution in the size of the lakes and a concentration of their waters into small lakes of relatively high salinity.

There is no reason to think that Pyramid and Winnemucca Lakes were any exception to this general rule. When the diminishing Lahontan reached the level of Emerson Pass between the Pyramid-Winnemucca and Smoke Creek Basins, the parts of the lake on the two sides of the divide presumably fell so

rapidly and at so nearly the same rate that there was no appreciable overflow from one to the other. The Pyramid-Winnemucca Lake continued its fluctuating process of desiccation and became more and more saline. This would not exterminate the fish, which Jones and Antevs cite in support of their respective views. At the mouth of the Truckee and along its lower course there must always have been regions of gently moving fresh water which were sufficiently lake-like to preserve the lacustrine fauna that still exists. An illustration of this is seen at Lopnor in Chinese Turkestan. There the Tarim River is finally lost in the intensely salt water at the eastern end of the lake of Lop. But between the salt water and the river there are extensive reed beds and small lake-like openings where the water is practically fresh and the Loplik fishermen catch abundant fish. Similar conditions may easily have allowed the peculiar fauna of Lahontan to survive, at the lower end of the Truckee River, even when Pyramid Lake was much smaller and more saline than at present.

The concentration of the combined lake which filled both the Pyramid and Winnemucca basins presumably reached a maximum when the divide between the two basins was exposed. As soon as that happened a stream presumably flowed from Pyramid to Winnemucca, or occasionally the other way, for a river which had hitherto maintained both lakes would necessarily cause either one alone to overflow. Such an overflow, of course, tends to remove the salts from one of the lakes, and thus one or the other may have been freshened while the other was growing more saline. The topography and the recent history of the region both indicate that the flow from one lake to the other is practically always from Pyramid to Winnemucca, the reverse being only a very temporary occurrence. Thus Pyramid Lake apparently was freshened. At the same time Winnemucca must have been growing more saline, especially if the climate reached a stage where the level of Winnemucca was decidedly below that of Pyramid for some time.

FRESHENING OF WINNEMUCCA LAKE.

In order to account for the fact that Winnemucca Lake as well as Pyramid Lake is now comparatively fresh, it seems to be necessary to assume that at some time the climate became so dry that the Truckee River was unable to maintain Pyramid Lake even at its present level. Hence that lake presumably fell so low that it no longer discharged any water to Winnemucca Lake. Even as late as 1862 essentially this condition prevailed for a short interval. If it continued a century or two, Pyramid Lake would fall distinctly below its present level and its waters would increase in salinity. Winnemucca, meanwhile, might become completely dry. Its present relatively slight salinity seems explicable only on the assumption that it not only became completely dry, but remained dry long enough so that the salts which it must have laid down on its floor were covered by alluvial deposits to such a depth that they were not redissolved when the lake was once more filled. This would not take a long time, for the lake is only 5 miles wide at most; it is surrounded by fairly high and quite steep mountains; and the streams which flow into it, aside from the Truckee, are highly torrential. The torrential quality of the streams was presumably increased by the aridity, for it is generally the rule that the drier a region, the more torrential its rainfall and the worse its temporary floods. Moreover, the extreme dryness, following

a period which seems to have been moister than at present, would diminish the vegetation on the mountains and thus make it especially easy for the rains to wash away the soil. The amount of such soil was presumably greater than now, for the slopes must have borne much more vegetation than at present during the comparatively moist glacial and post-glacial epochs. Such a cover of vegetation would tend to hold the soil in place and allow it to become relatively deep. Hence we infer that a few centuries of extreme aridity would permit the salts of the lake to be buried too deep to be redissolved.

As to the date of this dry period we can not speak with certainty. It will be remembered that according to Jones (p. 42) the period required for the accumulation of the salts in Pyramid and Winnemucca Lakes ranges from 2,450 to 3,880 years, provided the salts were derived only from the Truckee River. On the basis of the differences between earlier and later analyses of the water he gets a period of 1,956 to 2,400 years. If allowance is made for the salts carried in by smaller streams in addition to the Truckee River, the first two figures will be considerably reduced. Another reduction of unknown importance must be made to allow for the fact that Winnemucca Lake may not have been completely desiccated, or the salts deposited by it may not have been completely covered by alluvium. On this basis the time since the desiccation of the lakes is reduced to considerably less than 2,000 years. It will be remembered that in our study of tree growth we found a fairly high correlation between the trees and the rainfall at Winnemucca. This indicates that the fluctuations in rainfall in the Big Tree region and in the Pyramid-Winnemucca basin are similar. In that case it seems probable that the first desiccation of Winnemucca took place during the dry period which culminated about 650 A. D. according to the trees. That is the earliest time when there is any evidence of so dry a period within historic times, either on the basis of tree growth or in the fluctuations of the Caspian Sea as described in *The Pulse of Asia*. It is quite possible, and indeed probable, that the lake was again desiccated during later dry epochs, such as the thirteenth and perhaps the late sixteenth centuries of the Christian era, but that does not alter our general argument.

RECENTLY DESICCATED LAKES IN OREGON AND NEVADA.

The drying up of lakes is by no means an uncommon event in the Basin-and-Range province. Waring¹ reports that no longer ago than 1887-88 Silver Lake in southern Oregon became dry after having dropped about 10 feet in 6 years. "Its bed was taken up for farms, and one season's crops were gathered before the lake again filled." By 1906 the lake again appears to have risen 13 feet. Such rapid changes illustrate the inconstancy of a lake whose water supply is derived from short, local streams with no high mountains to nourish them.

Not far from Silver Lake, two other salt lakes without outlets, Abert with an area of 60 square miles, and Summer, 70 square miles, are said to have shrunk little, if at all, when Silver Lake became dry. Each of these, like Pyramid Lake, derives its water from a mountain river. Both are very shallow, averaging only 5 feet over large areas, although Abert is reported to be over 25 feet deep on its east side. Abert and Summer Lakes are important

¹ A. G. Waring, U. S. Geol. Survey Water Supply Paper, No. 220, 1908.

for our present purpose because "a conservative estimate" of their age "based on their concentration and area, the composition of confluent waters, and the rate of evaporation heretofore assumed, is 4,000 years." It is quite possible that the lakes are recent pools, and that the salt and soda deposits of early quaternary Chewaucan Lake lie buried beneath them. There is no indication that the lakes were freshened by overflowing, nor do the published statements give any hint that one of them overflowed into the other. So far as evidence is yet at hand, both appear to have dried up, and thus to have been freshened. It must not be supposed that this indicates a dry period 4,000 years ago. It merely means that the period since desiccation can not be *more* than 4,000. It may be much less, and probably is. Abert and Summer Lakes lie out in the middle of a plain at some distance from the mountains. The dry floors of such lakes can not be sheeted over with alluvium nearly so quickly as can those of a mountain-girt lake like Winnemucca. Hence it is probable that a considerable amount of salt has been redissolved from the deposits laid down when the lakes dried up. Since the seventh century appears to have been distinctly the driest period during historic times in Asia and likewise in the Big Tree region, it is not improbable that Abert and Summer Lakes, as well as Winnemucca, dried up at this time; although we can not assert this with any positiveness.

Walker Lake is another which appears to have dried up in recent times, as Jones (p. 46) and Antevs (p. 102) both show. The time since this lake was last freshened may be judged from the fact that Jones estimates that it would take the Walker River, the main feeder of the lake, 1,163 years to supply the present chlorine in its waters, while the rate of evaporation suggests that it would take 1,300 years to concentrate the chlorine if the lake remained at its present size. When allowance is made for salts derived from other sources than the Walker River and from the solution of materials laid down at the time of desiccation, the period since the last desiccation of Walker Lake becomes less than a thousand years. Perhaps the lake dates from the dry period indicated by the sequoia trees in the thirteenth century A. D. It should be noted that Winnemucca, Abert, and Summer Lakes may also have been dry at this time, and probably were. In assigning their desiccation to the seventh century we are merely indicating the earliest method when such an event seems likely to have taken place.

RECENT OVERFLOW OF OWENS LAKE.

One other lake should be mentioned in this connection. The waters of Owens Lake in southern California, and of the river of the same name which supplies most of its water, have been analysed with unusual care because the river has been used for the Los Angeles water supply. According to Gale¹ the analyses show that the river, at the point where it was tested, would require 4,200 years to supply the chlorine now in Owens Lake and 3,500 to supply the sodium. These determinations are based on many analyses continued over a long period, and hence are much more reliable than those of the other lakes. Owens Lake does not now overflow, but a series of fresh strands and an old outlet channel show unequivocally that the lake overflowed not long ago.

¹ H. S. Gale, *Salines in Owens, Searles and Panamint Basins, southeastern California*, U. S. Geol. Surv. Bul. 580-L.

Hence Gale concludes that "4,000 years ago or considerably less" the lake stood at the outlet level, 180 or 190 feet higher than at present, and overflowed to Searles Lake where another remarkable series of strands marks a great number of steps in the desiccation of the region. The reason why Gale says 4,000 years "*or considerably less*" is that the analyses of Owens River omit the lower third of the drainage area of Owens Lake. This is the part where the waters of Owens River and of the other smaller streams flow most slowly, and where they traverse old lake clays which are more saline than the rocks among the mountains. In addition to this, as Gale carefully points out, no allowance is made for the fact that when the river was larger, as must have been the case when the lake was full, its waters must have carried more salts in solution than now, even though the percentage of salts may have been less. When allowance is made for all these factors, the time since the last overflow of Owens Lake can scarcely have been more than 2,500 years, and more probably was not far from 2,000. Since the lake was freshened by overflow and not by desiccation, there is no uncertainty due to the re-dissolving of saline deposits laid down on the bottom of the lake. Hence 2,000 or 2,500 years seems to be the outside limit to which we can push back the time when Owens Lake expanded to two and one half times its present area and overflowed to Searles Lake.

STRANDS OF OWENS LAKE.

Now it happens that Owens Lake lies only 50 miles from the region where grew most of the sequoias used in our previous study. The main ridge of the Sierra lies between the two regions, but the general fluctuations in rainfall are closely similar. We have seen that variations in the growth of the sequoia appear to be mainly dependent upon precipitation, and that the sequoia curve must be in large measure a curve of precipitation. Hence it is not only legitimate, but essential to inquire how far the fluctuations of tree growth agree with those of the lake. At Owens Lake there are four chief series of strands. The uppermost is a huge gravel beach, or series of beaches and bars at the level of the outlet. It doubtless represents the approximate level at which the lake stood for thousands of years, not only during the glacial period, but most of the time since then, except perhaps for brief dry intervals and the present relatively dry period since the Christian era. After this main strand was abandoned for the last time there must have been a dry period of considerable severity. The evidence of this consists of a number of gravel fans which have been built directly across the main strand and extend downward to or perhaps below the present lake level. We may tentatively suppose that these fans represent the dry period indicated by the trees as culminating about 650 A. D., for that seems to be the only time when they could have been formed. Judging by the probable desiccation of Lakes Winnemucca, Abert, and Summer, at this time, and also by the fact that dated human structures indicate a remarkably low stand of the Caspian Sea at the same period,¹ we may conclude that Owens Lake then stood lower than now.

The next stage in the history of the lake was a rise of level part way toward the old strand at the outlet. It then formed two small strands, superposed upon the fans formed in the preceding dry period. The strands of this

¹ Ellsworth Huntington, *The Pulse of Asia*, 1907.

second series are not gravelly like their predecessors, but faint and sandy as if the lake did not stand long at that level and also as if the winds were not strong. If the trees may rightly be used as a guide, these strands date from about 1000 A. D. How far the lake receded in the following epoch can not be determined, but gravel fans were once more deposited, covering parts of the weak strands just as the main strand had been covered by larger fans during an earlier dry epoch. Hence we are quite sure that the lake must have fallen to a level lower than that of the third strand, shortly to be described, and perhaps lower than the present level of the water. We infer that this dry period corresponds to the time when the trees grew especially slowly in the thirteenth century. Another period of heavy rainfall seems next to have ensued. This time the water did not rise so high as during the period which we have tentatively dated at 1000 A. D., but it rose high enough to form strands across fans that had been deposited during the preceding dry period which we have tentatively assigned to the thirteenth century. We infer that this third strand corresponds to the rapid growth of the trees culminating in 1350 A. D. The character of the strand is especially remarkable, because of the height, size, and coarse gravelly character of the beach. These characteristics suggest that although the period of heavy rainfall did not last long enough, or was not severe enough, to raise the lake to a very high level, the storms, for a few score years perhaps, must have been unusually severe and the winds very high. Now this, as shown in *Civilization and Climate*, and still more in *Climatic Changes*, appears to be one of the most noteworthy characteristics of the period of climatic stress which the trees indicate as culminating about 1350 A. D. We have abundant evidence to this effect in China, central and western Asia, Europe, Iceland, and Greenland. The contrast between the third beach at Owens Lake and the faint double beach above it may be an important confirmation of the reliability of our method of correlating tree growth and lake levels. The lowest of the four series of strands at Owens Lake is sandy and small compared with the large gravel bar which we have assigned to 1350. It was evidently formed under different conditions. Presumably the lake fell to a low level about 1500 A. D., as suggested by the trees, but the dry period thus indicated was probably too mild and too short to allow the formation of gravel fans of any great magnitude. Presumably the lake soon rose to form the highest of the little group of strands forming the lowest series, and then fluctuated back and forth, forming the others during the seventeenth and eighteenth centuries. One of the most significant facts about Owens Lake is that it differs from the other freshened lakes in showing some evidence as to the approximate dates of the successive levels of the water during the last 2,000 years more or less. It also, though less clearly, indicates dry periods like those during which we infer that the other lakes became desiccated. But all of the other lakes also have fresh strands above their present level. Thus the lakes of Oregon, Nevada, and California, like the trees of the Sierra, suggest distinct pulsations of climate as well as a general desiccation during the past 2,000 years or so.

RUINS OF SOUTHERN NEVADA.

Human as well as physical evidence seems also to indicate recent desiccation. The area of Clark County at the southern tip of Nevada almost exactly equals that of Massachusetts. The total population, however, amounted to only 4,859 in 1920 in contrast to 3,852,356 in Massachusetts. The main reason for this contrast is that Clark County lies in the driest part of the United States, its western border being only 50 miles from the central depression of Death Valley. In the eastern lowlands, where most of the people live, the total rainfall averages somewhat over 5 inches per year. As less than half of this falls during the 6 months from April to September, agriculture is impossible without irrigation.

Until recently southern Nevada was generally supposed to be so dry that even the hardy Pueblo Indians could not establish permanent towns. The local inhabitants, however, have long been familiar with the remains of a number of Indian towns, especially a ruin some six miles long in the Muddy River Valley. In 1924, under the auspices of the Museum of the American Indian at New York, Harrington found that this ancient "Pueblo Grande de Nevada" probably dates back to the pre-Pueblo period some 2,000 years, and probably had a population of several thousand. It was occupied for generation after generation, irrigation was extensively developed, and the stage of culture was relatively high.

In order to understand the significance of these facts, compare the white man's means of getting a living with those of the Indians. At Las Vegas, for example, the population of the only real town in Clark County falls into four groups. (1) The largest group consists of railroad people, for this little town is the most important railroad center in the whole southern half of Nevada. (2) Another group, probably the next in size, consists of cattle ranchers. (3) Next come the miners, especially those engaged in the borax mines. All of these three groups obviously depend on resources unknown to the ancient Indians, or at least unused by them. (4) The smallest of the communities at Las Vegas is the farmers. Indeed the whole of Clark County contained only 162 farmers in 1919. But even they depend largely on horses, cattle, sheep, pigs, chickens, oats, hay, barley, orchard fruits, grapes, and especially wheat, all of which were unknown to the Indians. Moreover they are aided by iron tools, complicated machines, engines, and other appliances, whereas the Indians had nothing but hand-made tools of wood, bone, and stone.

Now compare the irrigated area of to-day with the supposed population of the past. In 1919 the total irrigated acreage in Clark County was 5,206 acres, of which approximately 2,800, as nearly as can be estimated from the Census reports, was in the valley of the Muddy River. From at least a tenth of this, to judge by the Census reports of acreage, no crops appear to have been reaped. Thus 2,500 acres represents about the area that the white man, with all his machines and engineering skill, now finds it worth while to use for irrigated crops in the Muddy River Valley in an ordinary year, such as 1919. Unless he builds irrigation works of much greater magnitude than has yet been attempted, he can not use much more. Could the ancient Indians use as large an area? I doubt it. Our modern farmers rely mainly on winter cereals and hay. These together account for about three fourths

of the area from which crops are reported in the census. They are well adapted to a dry region like southern Nevada where most of the rain comes in winter, because they can be planted in the autumn. That permits them to grow during the relatively warm winter, and finish their growth in the spring when the water supply in the streams is at a maximum. The poor Indians, on the other hand, had no winter crops. Their corn, beans, and pumpkins could not be planted until the time of comparatively high water in the spring, and had to make most of their growth during the hot dry summer when water is very scarce. There is no reason to think that the Indians made reservoirs of any appreciable size, for no evidence of this has been found, and it is too difficult or expensive a task to be worth while even at present. Hence, if the white man to-day in an ordinary year can raise crops on only about 2,500 acres in the Muddy River Valley, it seems probable that the Indians, with their summer crops, could utilize scarcely more than half as much. In dry years the available area would of course be less. At Logandale, near the Indian ruins, 8 out of the 14 years for which data are at hand had a rainfall less than that of 1919. One year the amount fell to only 2 inches. Thus under present conditions of climate, it is hard to see how people like the primitive Pueblo Indians could permanently count on much more than 1,000 or at the outside 2,000 acres of land. Such an area would be adequate for a population numbering only hundreds rather than thousands. With crude methods such as the Indians employed, the average area required to support an individual comes nearer to two or three acres than to a half or a tenth of an acre. If, however, the climate 2,000 years ago, more or less, was distinctly more rainy than now, the whole difficulty vanishes. This case, like many others, illustrates the fact that a knowledge of changes in physical conditions is an almost essential requisite to the correct interpretation of history.

This terminates our survey of the evidences of climatic changes in post-glacial times. The most significant feature of the whole study is that the greater the amount of detail which we are able to obtain, the fuller become the evidences of a great number of climatic pulsations. Each of the criteria employed by the authors of this book points to the same conclusion. No matter whether we study glaciers, the rise and fall of lakes, the chemical composition of lakes, the deposits of lakes, the alluvial fans at the base of mountains, the growth of trees, or the history of ruins, the evidence leads to the conviction that in general the climate of the southwestern United States was moister and cooler in the past than at present, but that, in both prehistoric and historic times, there have been marked fluctuations. The abundant evidence of dry periods as well as moist brings into strong relief the fact that *variability* has been the dominant quality of the earth's climate throughout the human period. Even within 2,000 years we appear to have had variations which at one extreme caused Owens Lake to expand to two and one half its present size before it overflowed, and which might have made it still larger if there had been no overflow. At the other extreme those variations seem to have led to the desiccation of many lakes, including Walker, Abert, Summer, and Winnemucca. Such variability can scarcely fail to have had a marked effect upon the habitability of the country, not only for plants and animals, but for man.

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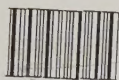
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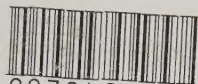
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